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Advanced Urban Energy Planning:

an interdisciplinary approach to improve heat decarbonization assessments

Chiara Delmastro

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Supervisors
Prof. S.P. Corgnati, Politecnico di Torino, Supervisor
Eng. M. Gargiulo, E4SMA, Co-Supervisor
Prof. A. Carpignano, Politecnico di Torino, Co-Supervisor

Doctoral Examination Committee:
Prof. E. Ahlgren, Chalmers University
Prof. E. Fabrizio, Politecnico di Torino
Dr. L. Munuera, International Energy Agency
Prof. A. Kindinis, Université Paris-Est
Prof. J. Kurnitski, Tallinn University of Technology

Politecnico di Torino

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Declaration

I hereby declare that, the contents and organisation of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data. Part of the work described in this Ph.D. dissertation was also previously published in the following Journals, further reported in Appendix A of this thesis:

Paper	Details
I	Torabi Moghadam S., ***Delmastro C.***, Corgnati S. P., Lombardi P. (2017). **Journal of Cleaner Production**, 165, 811-827.
II	***Delmastro C.***, Mutani G., Corgnati S.P. (2016). **Energy Policy**, 99, 42-56.
III	Becchio C., Corgnati S.P., ***Delmastro C.***, Fabi, V., Lombardi, P. (2016). **Sustainable Cities and Society**, 27, 324-337.
IV	Mutani, G., ***Delmastro, C.***, Gargiulo, G., Corgnati, S.P. (2016). **Energy Procedia**, 101, 384-391.
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VI	***Delmastro, C.,*** Martinsson, F., Dulac, J., Corgnati, S.P. (2017). **Energy**, 138, 1209-20.
VII	***Delmastro C.,*** Mutani G., Perassi, S. (2016). **International Journal of Heat and Technology**, 34 (2), 266-276.
VIII	***Delmastro C.***, Martinsson, F., Mutani, G., Corgnati, S.P. (2017). **Procedia Engineering**, 198, 386 – 397.
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X	Borchiellini, R.; Corgnati, S.P.; Becchio, C.; ***Delmastro, C.***; et al (2017). **International Journal of Heat and Technology**, 35 n. Specia, 196-204.

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Chiara Delmastro

Torino, 2018

"Teach me the art of small steps" wrote Antoine de Saint-Exupéry.

I dedicate this thesis to my parents who always taught me to face daily difficulties with patience and simplicity.

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Abstract

Urban areas have been recognized as the heart of the decarbonisation process, being potential drivers of sustainable or unsustainable paths. The necessary transition to cleaner and more sustainable cities recently raised the research attention on the possible ways to perform urban energy planning. However, there is still not a well-recognized procedure and an agreed methodological framework to support urban energy planning, leading to inappropriate strategy definitions, directly focusing on the design of a pre-defined plan.

This thesis has the primary objective to contribute in providing a theoretical-methodological framework to support urban energy planning by exploring, applying, adapting and combining with other disciplines, the principal energy system planning methods and tools.

A review of scientific literature was performed to identify the state-of-art significant limitations on which the thesis was structured. Without seeking to replace other existing modelling approaches and without presupposing a full knowledge in the different research disciplines, this Ph.D. dissertation provides a basis for understanding how the weaknesses of the different approaches can be rectified by the strengths of others to move beyond traditional urban energy planning applications focused on the built environment. Comprehensive energy system methods and tools are necessary at the planning stage to quantitatively consider interactions among sectors and demand and supply options over long-term horizons. Nevertheless, the thesis confirms that while they are incredibly useful for planning purposes, they cannot be used alone for urban applications and should be combined with other methodologies. This need is mostly related to the necessity of disposing of a detailed and highly disaggregated description of the demand and of the spatiality to deal with specific urban needs (critical areas, liveability, built environment constraints). In particular, spatial analyses are fundamental in urban planning to considerably improve the quality of planning and decision-making processes through intuitive visualization maps. Furthermore, the involvement of stakeholders is key to the success of the planning procedure: they speed the data collection process, support definition of assumptions and a shared city vision (qualitative evaluations).

Given the complex nature of urban energy planning, an interdisciplinary and integrated methodological procedure - based on the actions of knowing, understanding and planning – is therefore proposed. The procedure combines building physics, energy planning and territorial analyses to create a preliminary methodological background able to deliver technical, financial and environmental insights for the definition of energy plans. The proposed methodological framework was applied to a case study that fixed the research boundaries to the demand and supply side of the urban built environment of district-heated cities. The case study, on the one hand, provides numerical evidence to results and on the other hand offers a theoretical background for guiding urban planners, researchers, and decision-makers in future urban planning applications.

As a result, the proposed integrated and comprehensive framework provides evidence of the multiple benefits of taking into account synergies between demand and supply, particularly in term of avoided additional investments. The scenarios analysis confirms that ambitious environmental targets can be reached at reasonable added costs if investments are appropriately channelled. The suggested research advances in urban energy planning will allow achieving more informed assessments of appropriate strategic investments, their life-cycle costs, and energy/ environment ambitions. All the recommended planning phases are fundamental, and the author suggests to push future research and practices to enhance the procedure by dividing it into a planning stage (knowing & understanding/ planning/ prioritizing & deciding) and into an operational phase (designing/acting/ monitoring & informing), leading to a bi-directional flow of information between planning and operational models.

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Chapter 1

Introduction

In recent decades, urban areas were recognized as major contributors to carbon emissions being responsible for more than 70% of energy-related emissions (International Energy Agency, 2008). 60-80% of global final energy use is associated with urban areas (Grubler et al., 2013). Therefore, urban areas play a significant role in the transition toward low carbon development and a cleaner future (International Energy Agency, 2016). This transition requires the definition of a set of strategies taking into account both national priorities and specific local characteristics and needs.

However, there is still not a well-recognized procedure and an agreed methodological framework to support urban energy planning with the potential risk of leading to inappropriate strategy definitions directly focusing on the operational design of a pre-defined plan.

1.1 Problem declaration

For supporting the strategic long-term planning process, energy planning techniques were developed since the late '50s. At that period, the primary purpose of energy planning was to help the various energy supply companies to make appropriate decisions to solve the massive growth of the energy demand (Herbst et al., 2012). The purpose of planning evolved starting from the 1990s together with the increase of sustainability and environmental concerns, shifting the focus towards the relation between energy and environment (Fleiter et al., 2011). During those years, planning analyses were mostly focused on large scale (national or multi-national) applications, but currently, urban energy planning has been recognized as necessary to face urban energy challenges (Mirakyan et al., 2009).

Urban energy planning is considered a multidisciplinary and complex problem (Albeverio et al., 2008). In fact, it involves multiple actors and different sectors requiring a comprehensive vision of urban sustainable energy policies and a strong co-operation between national and local governments. While large-scale energy planning methodologies are well consolidated, local application still faces methodological and technical challenges, coupling the traditional energy planning issues together with the specific complexity of the local reality such as dealing with multiple and diverse stakeholders and the need of high level of territorial details (physical, logistic, social constraints; energy demand distributions etc.). Due to the complexity of this research field and to the unattained agreement on a common methodological framework, many types of research are nowadays focused on exploring which are the possible ways to face urban energy planning.

This thesis has the primary objective to contribute in providing a theoretical framework to support urban energy planning by exploring, applying, adapting and combining with other disciplines, the principal planning methods, and tools.

1.2 Research background

This introductory section synthetically frames the role of urban energy planning in research, mostly regarding urban energy challenges and sustainable energy planning in urban areas. In addition, it presents a key applicative challenge that represents the thesis case study focus.

1.2.1 The urban energy challenge: sustainable planning in the urban built environment

At the 21st Conference of the Parties (COP21), a strong and broad agreement on climate change mitigation goals was reached with the ambition of maintaining the world temperature increase below 2°C. To meet this objective current energy trends need to be re-shaped into low-carbon ones cost-effectively to be financially profitable and consequently affordable. To such purpose, identify priority areas for intervention may be extremely important to succeed.

Urban areas have been undoubtedly recognized as key elements for fostering sustainable energy paths. In 2013, more than 50% of world's population lived in cities, about 80% of global GDP was generated in cities, two-thirds of primary energy needs was consumed by cities, accounting 70% of global carbon dioxide emissions

(International Energy Agency, 2016). In addition to these impressive data, driven by the urbanization process and economic growth, the global urban energy demand is set to grow in the near decades. Estimates from the IEA expect to have 6.3 billion urban inhabitants (2/3 of total) in 2050 and a 70% urban primary energy demand grow from 2013 to 2050 (International Energy Agency, 2016). Therefore, cities have a decisive role in promoting a sustainable change with excellent opportunities to improve citizen lifestyle and to reduce pollution and carbon emissions levels (direct and indirect). Nevertheless, at the same time, without proper strategies, urban areas may also be drivers of unsustainable paths. Essential challenges need therefore to be faced by urban areas by defining adequate policy development strategies. There is no a standard solution fitting every urban reality, but a structured and systemic approach to city planning may help decision-makers to choose the "best" alternative between different scenarios involving every level of the urban energy system (from primary energy production to consumer, from transport to buildings).

The raising attention to urban needs and its sustainable development drive the different communities to take action. In particular, thanks to Covenant of Mayor Initiative (European Commission, 2017), many European municipalities developed their energy plan SEAP - Sustainable Energy Measures Plan (Delponte et al., 2017). This Initiative promotes the vision to 2050 of "accelerating the decarbonization of their territories, strengthening their capacity to adapt to unavoidable climate change impact, and allowing their citizens to access secure, sustainable and affordable energy" (European Commission, 2017). This initiative confirms that actions start to be implemented to accelerate the urban low-carbon transition.

From the screening of a wide range of urban energy planning practices, both real (European Commission, 2017) and research-oriented (Torabi et al., 2017), the major limitations in current urban planning practices emerged. In particular, most of the urban energy planning practices are not driven by urban specific problems but inspired by other experiences looking like short-time initiatives. Also, they are not supported by a systemic and well-structured planning procedure. Additional efforts need therefore to be devoted to urban energy planning methodologies.

1.2.2 The role of buildings and district heating in future energy systems

In response to global climate change objectives, specific goals have been set up by the European Union to cut carbon emissions with respect to 1990 levels of 40% by 2030 and of 80% by 2050 (European Commission, 2011a). All the sectors may significantly contribute to the required energy transition. Nevertheless, in 2013 the building sector was responsible for 30% of global final consumptions (International Energy Agency, 2016). This information coupled to the high energy savings potential associated to the "old" European buildings (approximately 40% of Europe's building stock predates the 1960s) clarify why higher emissions targets are required by the building sector: about 90% of emissions reduction to 2050 (European Commission, 2011a). Urban buildings are responsible for more than 60% of building final energy consumption (International Energy Agency, 2016). Indeed, not surprisingly, the building sector is a key sector in urban areas, being the objects constituting the city itself.

Differently from emerging economies that are experiencing an explosion of new constructions, European new buildings represent only about 1% of building stock; furthermore, most buildings present today in Europe will still be standing in 2050 (Constantinescu, 2011). Therefore, the retrofit of existing buildings with its significant potential for both cost-effective CO_2 emissions mitigation and substantial energy consumption reduction represents an extraordinary opportunity for improving urban environmental quality (“Energy retrofit to nearly zero and socio-oriented urban environments in the Mediterranean climate,” 2014) and it can be seen as one of Europe's most significant energy resource playing a crucial role in hitting 2050 targets.

Nevertheless, the building sector may cut carbon emissions even through energy efficiency measures in the supply and new energy supply options. In particular, for areas with high heat densities, district heat (DH) may represent an attractive solution since it can take advantage of the local excess heat and renewable energy sources, as well as high-efficiency heat generation technologies such as combined heat and power (CHP). Benefits related to the development of DH networks can be found in the work of (Connolly et al., 2014). Moreover, it has been recognized that heat demand in Europe is sufficient for promoting the development and expansion of DH systems (Persson and Werner, 2011).

It is plausible to assume that in areas where DH is already present or is planned, variation in thermal demand will occur as building energy efficiency improves over time. Two central deliberations can be considered: (i) at a certain point, energy efficiency measures in buildings will stop being cost-effective relative to the cost of heat, and (ii) variation of thermal demand will impact the operation and generation strategies for DH and could influence any new investment strategies. Finding synergies between energy efficiency strategies in building renovation and DH supply has been identified as fundamental to the success of urban heat strategies (International Energy Agency, 2016). In cities with existing DH networks, this powerful synergy is central (Truong et al., 2014). In fact, while energy savings obtained from DH network extensions seem an attractive solution from an energy and environmental perspective, finding economically viable solutions is still a challenge (Sayegh et al., 2016).

Being this issue considered as one of the key emerging European urban challenges (Sayegh et al., 2016), the case study of the thesis has the planning objective to **find economic and energy options that combines the potential expansion of district heating (DH) systems coupled with building energy savings,** and with a broader perspective**, to delineate a methodological framework to shape urban heat strategies, including district heating.**

1.3 Research limitations and research questions

This thesis focuses on the actual limitations emerged from the state of the art on the topic of urban energy planning with the objective of highlighting proposals on how to overcome the existing barriers and highlighting future needs.

By looking at the developed energy plans and by exploring current literature, it is evident that **urban energy planning still lacks clear, standardized guidelines to support urban stakeholders in the definition of their energy plans**. The first research question is, therefore:

1) Which are current and future challenges and barriers in long-term urban energy planning? Which can be a theoretical framework to support this practice?

In particular, although the general awareness about the concepts of urban energy planning, sustainability, innovation and participation, urban **energy planning practices still lack a medium-to-long planning vision**. Actions are generally thought, designed and implemented looking at the short-term (e.g., 5 years plans) without a clear and comprehensive objective. Probably it is connected to shorter time frames of political mandates and lifetimes of people involved in projects. Nevertheless, both energy policies (involving new building codes, taxes, technologies penetration..) to be implemented and energy infrastructure to evolve require a long-term vision. Long-term analyses are therefore needed since the modification of an urban system, as well as the introduction of new market solutions, have a long time of response (Steidle et al., 2000). Furthermore, most of the current urban energy planning applications are single-sector focused, but urban areas are composed of multiple interconnected sub-systems. This fact leads current practices to **neglect some important cross-sectoral relationship of the energy system**, such as the effects of specific policies on the whole energy system (Harrestrup and Svendsen, 2014). A more comprehensive approach is therefore needed to catch system dependencies, with particular attention to demand-supply interactions. This planning aspect couples with urban needs such as embedding territorial and social constraints. Modelling urban energy systems calls for detail-based approaches (Mendes et al., 2011), in contradiction to traditional larger scale planning analyses. Consequently, the second research question is:

2) How to "adapt" long-term comprehensive energy system methods and tools to urban applications?

The third research question is related to the previous one:

3) Which are the strengths, weaknesses and main opportunities of the two main comprehensive energy system method/tool families (simulation and optimization approaches) in urban applications? How to couple them with building energy modelling?

These three research questions lead this thesis to explore and propose a theoretical framework to support urban energy planning over long-term horizons. The related learning outcomes may help to re-conceptualize urban energy planning practices, leading the way for new comprehensive approaches. Accordingly, this dissertation is expected to be very useful for all urban actors including, in particular, new practitioners, researchers, and decision-makers working in this topic.

To answer these research questions using quantitative evaluations, a comprehensive urban research question is proposed.

4) Are comprehensive energy system methods and tools suitable to support holistic heat decarbonisation strategies in urban areas (involving building retrofit and new heat generation technologies)?

Structure of the thesis

This Ph.D. thesis is structured into 8 chapters aiming at answering the identified relevant research questions.

Chapter 1 (Introduction) and Chapter 2 (Overview of energy planning tools and methods) are dedicated to the actual international state of the art related to urban energy planning. The literature screening was fundamental for identifying the limits in current research and for setting the theoretical bases on which the whole thesis relies. The scope of these chapters is to inform about urban energy planning techniques and the related major limitation at the urban scale.

Chapter 3 (Investigation approach) focuses on the narrative description of how and why the different methodologies are combined and applied during the thesis. The scope of this chapter is to help the reader in understanding the organization of the thesis and the application of some methods and tools.

Chapter 4 (Preparation and orientation phase), Chapter 5 (Detailed energy modelling phase: simulation approach) and Chapter 6 (Detailed energy modelling phase: optimization approach) represent the core of the thesis. The different methodologies are combined and applied to answer the research questions and defining a methodological framework to support urban energy planning over long-term horizons.

Chapter 7 (Discussion) and Chapter 8 (Conclusions) discuss the core research questions of the thesis and provide solutions, reflections and insights to enhance urban energy planning practices. In addition, they describe the key takeaways, innovation and research contributions provided by this thesis.

Three Annexes are at the end of the thesis. Annex A reports the abstracts of the published papers during the thesis completion, while in Annex B the schematic of the Reference Energy System (created in Chapter 4) can be found. Annex C summarizes the principal activities (courses and seminars) attended during the Ph.D. program.

Chapter 2

Overview of energy planning tools and methods

2.1. Overview

This chapter provides the theoretical base that stands behind the adopted methodology in the thesis, further described in Chapter 3. Section 2.2 introduces background definitions to clear the basic terminology while Section 2.3 describes the most widely used quantitative methodologies (Figure 2-1).

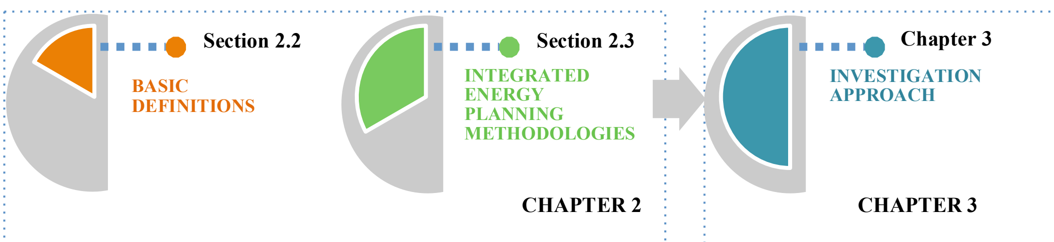


Figure 2-1: Chapter structure.

Declarations.

Part of the work described in this Chapter was also previously published in the following publication, further reported in Appendix A of this thesis: Torabi Moghadam S., Delmastro C., Corgnati S. P., Lombardi P. (2017). Journal of Cleaner Production, 165, pp. 811-827.

2.2. Basic definitions

This section introduces the main terminology adopted in the thesis in order to clarify some widely adopted concepts and understand the structure of the thesis.

The term "*Integrated Energy Planning*" refers to the definition introduced by (Mirakyan et al., 2009), as a long-term, model-based energy planning process. In this thesis, the Phases of integrated energy planning procedure were applied at an urban area. This procedure is divided into the following four major phases (Figure 2-2): Phase I: Preparation and orientations; Phase II: Model design and detailed analysis; Phase III: Prioritization and decision; Phase IV: Implementation and monitoring. The whole thesis is organized accordingly, but focusing on the technical related part. Therefore this thesis develops Phase I and Phase II and does not continue with Phase III and Phase IV. Concerning Phase II, the thesis is dedicated to the methodologies suitable to develop robust quantitative scenarios (combinations of actions and measures) and to provide to stakeholders the elements for excluding the options that are not suitable for the specific urban areas in terms of economic, environmental and energetic considerations, before entering in Phase III.

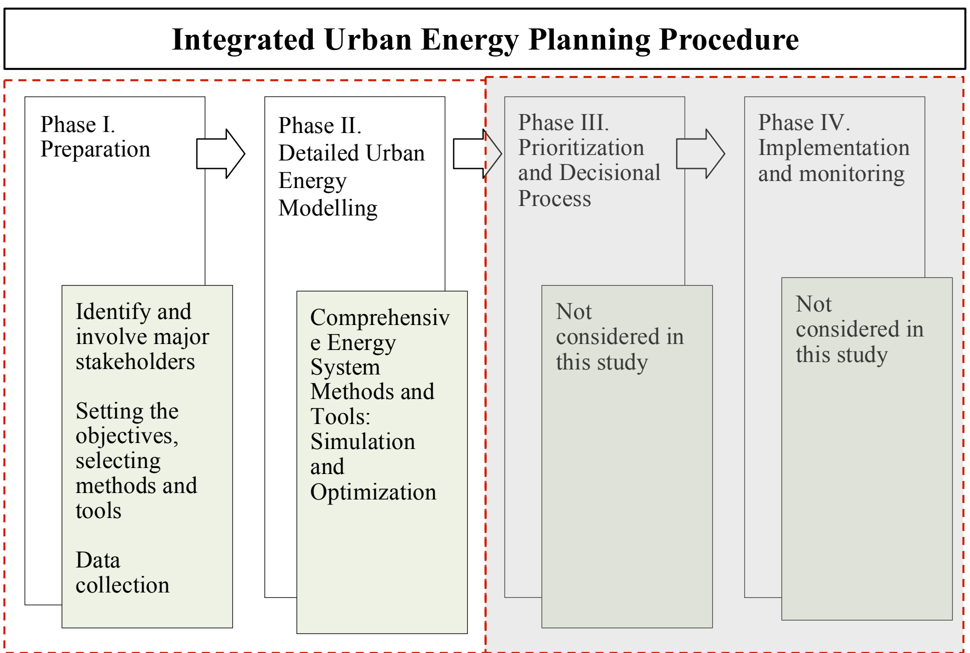


Figure 2-2: Integrated Energy Planning Phases. Adapted from (Mirakyan and De Guio, 2013; Torabi Moghadam, Delmastro et al., 2017)

"*Scenario*" is intended as a "tools for foresight" (de Geus, 1997) which help people to explore the future by displaying alternative sequences of events. Scenarios has been broadly used as an approach in the field of urban energy planning and have various classifications (Börjeson et al., 2006; Marien, 2002; Rotmans et al., 2000). In this thesis two main scenarios are considered: the “normative/prescriptive scenarios” that reason from specific targets which have to be achieved by taking values and interests into account and “explorative/descriptive scenarios” listing a set of possible alternatives without taking into account their desirability (configuration decided by users).

The *energy system* concept is defined as the combination of processes for “acquiring and using energy in a given society or economy”. Energy system analyses therefore consider the system as a whole, rather than its individual components. This concept comprehends both demand and supply side (Keirstead et al., 2012) including all the commodities flows, involved in all sectors and activities, and referred to the energy chain from final use to extraction. According to this definition, the thesis focuses on the building sector including demand and supply side and referring to the whole energy chain.

Urban energy systems refers to the “geographic-plus” definition of urban energy system proposed by (Keirstead et al., 2012). This definition considers the energy system as “*the combined processes of acquiring and using energy in a given society or economy*” and fixes the urban system boundaries as “*everything within the administrative boundaries plus easily traceable upstream flows, like electricity*”. In the thesis, the existing district heat plants were included in urban energy system even if outside the geographical boundaries of the city.

The term *Reference Energy System* (RES) refers to “a network description of the energy system that captures all the activities involved in the entire supply chain by taking the technological characteristics of the system into account” (Bhattacharyya and Timilsina, 2010). This approach is often associated to optimization methodologies as linear programming. The RES approach was used as a support of the modelling activities.

Comprehensive energy planning models refer to bottom-up models that aim at finding a suitable mix of energy supply and demand choices to support the local planning process from a cross-sectoral system perspective. In this way, a systems thinking approach focuses on how the matter being studied interacts with the other components of the system (Nakata et al., 2011). Among comprehensive energy planning models:

- a *simulation approach* "simulates the operation of a given energy system to supply a given set of energy demands" and "are operated in hourly time-steps over a one-year time-period" and
- a *scenario approach* that "usually combines a series of years into a long-term scenario" and "typically scenario tools function in time-steps of 1 year and combine such annual results into a scenario of typically 20–50 years" (Connolly et al., 2010).

(Mendes et al., 2011) further define *operation optimization* tools that "optimize the operation of some given energy system" (typically are simulation tools) and *investment optimization tools* that "optimize the investments in an energy system" (typically are scenario tools). In the thesis, the terms of simulation and optimization approaches are used and are coupled respectively to exploratory and normative scenarios.

The concept of "*Reference Buildings*" (RB) is intended as the "buildings characterized by and representative of their functionality and geographic location, including in- door and outdoor climate conditions'' (Corgnati et al., 2013). Their major purpose is to represent the average building stock characteristics. In this thesis, a set of Reference Buildings is identified in order to disaggregate the building sector and to identify building retrofit measures.

2.3. Integrated energy planning: quantitative methodologies to support Phase II

This section describes and comments on the main long-term energy system tools and methods together with the main building modelling approaches and some applications that were considered relevant for this thesis. The goal of this chapter is to provide a synthetic description of key strengths and weaknesses of the methodologies to support the choice of the ones to be adopted in the thesis. A first categorization classifies energy modelling into "top-down" and "bottom-up" (Kavgic et al., 2010; Swan and Ugursal, 2009). From a literature screening (Hitchcock, 1993; Martinez Soto and Jentsch, 2016), it can be understood that top-down analyses were mostly used for large-scale studies and are not considered suitable for urban applications. On the contrary, bottom-up models were recognized as suitable for urban analyses (MacGregor et al., 1993). In fact, modelling urban energy systems calls for detail-based approaches (Mendes et al., 2011). Consequently, the rest of the thesis refers to bottom-up models.

2.3.1. Comprehensive energy system tools and methods

Bottom-up comprehensive energy systems models are typically adopted for long-term runs (Herbst et al., 2012), and their application at urban and regional levels was introduced from 2000 in Steidle et al. (2000). As described in the Introduction, compared to large-scale applications, urban comprehensive energy system models require a higher focus on end-uses at a disaggregated level. In this study, models and tools are classified according to Connolly et al. (2010) and Timmerman et al. (2014) in Scenario, Simulation and Hybrid. It should be stated that, besides this classification, any individual model can have characteristics belonging to different model types making the categorization ambiguous (Hourcade et al., 2006).

Scenario models and tools, further referred as **optimization approaches**, determine the optimum set of technologies necessary to achieve, under constraints, a specific goal/target. They usually choose the mathematical approach of linear programming (LP), which means the optimization, under certain constraints, of a linear equation objective function. Urban models based on linear programming approach exist and can be coupled with spatial analyses. A GIS application of LP method was implemented by (Brownsword et al., 2005) to simulate spatial changes in energy demand profiles. Jennings et al. (2013) implemented an energy system model to support urban stakeholders in their choice among several building technologies. One of the main conclusions is to assess the long-term allocation of investments among several alternatives measures in both demand side and supply side. Other urban models based on LP were developed by Farzaneh et al. (2016) to address the urban electric deficiency and by Huang and Yu (2014) for the optimization of the urban heating energy system. Furthermore, there are many existing tools based on LP optimization that can be applied in urban areas. In particular, authors highlight the Integrated MARKAL-EFOM System (TIMES) developed by the Energy Technology System Analysis Program. TIMES is a multi-scale economic model generator suitable for medium (20-50 years) or long-term (up to 100 years) analysis (Loulou et al., 2005). It allows creating user-defined time-slices (Lewis, 2008; Vaillancourt et al., 2007). TIMES may require complementary interfaces for the simplification of the input/output data management (VEDA). A recent spatial analysis based on TIMES can be referred to the InSMART project (InSmart, 2015). Another important scenario tool based on LP-optimization techniques is the Open Source Energy Modelling System (OSEMOSYS) where the structure of time-periods is not multi-year, but a single year structure (Timmerman et al., 2014), with particular attention on the capability of modelling Smart Grids (Howells et al., 2011; Welsch et al. 2012). To the best of the author, any urban application of OSEMOSYS exists in current literature, but the structure of the model allows to be scaled for urban analyses.

Simulation models and tool, further referred as **simulation approaches**, “simulate the operation of a given energy system to supply a given set of energy demands” and “are operated in hourly time-steps over a one-year time-period”. As reviewed by Mendes et al. (2011), starting from the concepts of micro-grids and distributed generation some models were developed. The Hybrid Optimization Model for Electric Renewables (HOMER) is an open source energy system simulation model, which searches for the best mix of technologies able to minimize the total life-cycle cost. Some applications of HOMER can be found in Bahramara et al. (2016) and in the (NREL, 2016). It can be integrated with the Village Power Optimization of Renewable (ViPOR) to design the distribution grid of a local area. ViPOR requires a GIS import of spatial data, but can only be used for electric analysis, neglecting the thermal aspect. Another model focused on distributed generation is the Distributed Energy Resources Customer Adoption Model (DER-CAM). It is based on Mixed-Integer Linear Programming optimization techniques (Siddiqui et al., 2001). It aims at finding the most suitable combination of technological solution, their relevant size and operational profiles. A link with GIS tools to catch layout constraints and site new tech was proposed by (Edwards et al., 2002). With a similar purpose and approach, the Economic Evaluation of Micro-grids (EAM) was developed by (Asano and Bando, 2006). One of the most widespread simulation models is EnergyPLAN. It is a deterministic input/output simulation model that was built up for modelling the energy system at both national and regional scales (Ma et al., 2014; Østergaard, 2013). The model was designed to analyse regulation strategies of complex energy systems (Lund, 2007; Østergaard, 2015).

Hybrid tools and methods were developed considering the limitations of single approaches, hybrid models were developed to combine both scenario models with simulation models (Timmerman et al., 2014) and top-down models with bottom-up models. An example of a hybrid tool is the Long-range Energy Alternatives Planning (LEAP) which comes from OSEMOSys (Heaps, 2016). It describes both demand and supply side of the energy system considering all the economic sectors, tracking the environmental impact of each technological choice. It was widely applied in recent years at both national (Bautista, 2012) and urban and regional levels for comprehensive energy planning purposes (Kadian et al., 2007; Nojedehi et al., 2016; Winkler et al., 2006). The time horizon of LEAP is unlimited and characterized by a series of years, split into time slices.

Comprehensive energy system tools and methods aren’t widely used for urban energy planning yet and are therefore the main focus of the thesis. In order to focus on the two main modelling groups, hybrid models will not be further explored. Figure 2-3 summarizes the main identified Strengths, Weaknesses, Opportunities and

Threats of the simulation and optimization approaches, while Table 2-1 summarizes the most important characteristics of the described tools to facilitate the readers to choose the most appropriate one for their research.

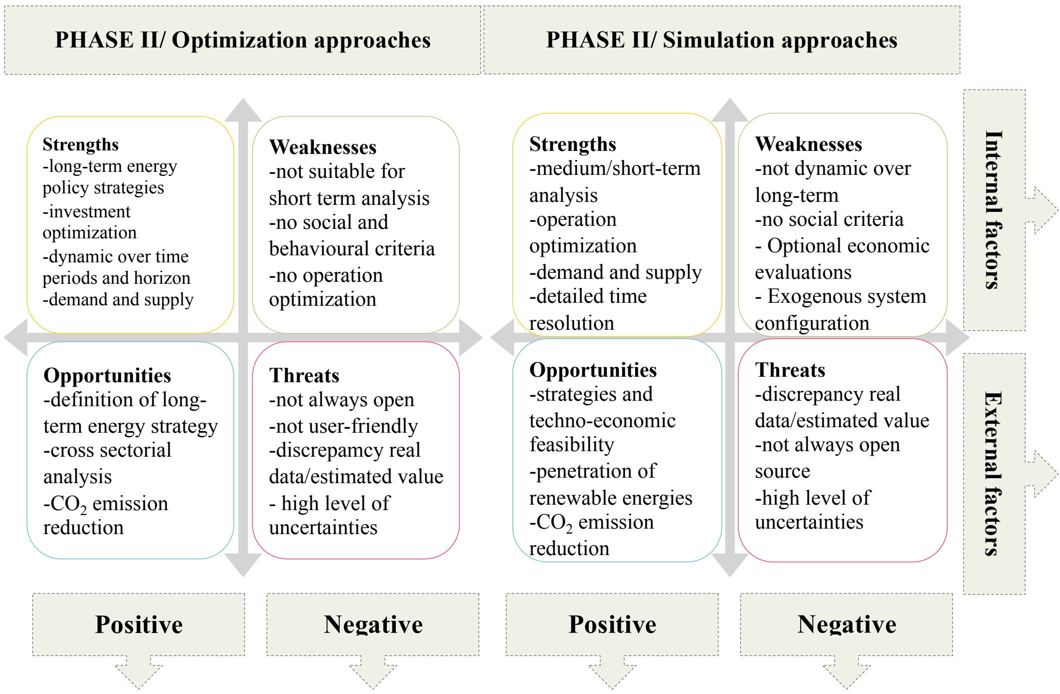


Figure 2-3: SWOT analysis of the two principal comprehensive energy system modelling approaches. Adapted from (Torabi Moghadam, Delmastro, et al., 2017).

Table 2-1. Overview of principal characteristics of bottom-up comprehensive energy system tools (Torabi Moghadam, Delmastro et al., 2017).*the code is open source, but it requires GAMS that is not.

Tool	TIMES	OSEMOSyS	ENERGYPLAN	DER-CAM	EAM	HOMER	LEAP
Developer	ETSAP	KTH, Stockholm Environmental Institute, IAEA, UK Energy Research Centre	Aalborg University	LBNL	University of Tokyo	National Renewable Energy Laboratory	Stockholm Environment Institute
Open Source	Yes*	Yes	Yes	Yes*	Not available to public	Yes	Dependent on type of users
Objective	Long-term energy policy strategies investigation	Long-term energy policy strategies investigation	Analysing regulation strategies of complex energy systems	Feasibility and dispatch optimization of distributed generation.	Appropriate sizing of a microgrid to be economically feasible	Best mix of technologies to minimize the total life cycle cost.	Energy policy analysis and climate change mitigation assessment
Type of tool	Scenario/ partial equilibrium	Scenario	Input/output simulation model	Simulation	Simulation	Simulation	Hybrid
Approach	Linear Optimization	Deterministic linear optimisation	Analytical programming	MILP/GAMS-CPLEX	MINLP	Accounting	Accounting/ Simulation
Type of optimization	Investment	Investment	Operation	Operation and investments	Operation and investments	Operation and investments	Operation and investments
Spatial Coverage	User defined	User defined	User defined	Local level	Local level	Local level	User defined
Covered Sectors	Energy System and Energy Trading	Energy system	Energy system	Heat and Electricity, micro-grids	Heat and Electricity, , micro-grids	Heat and Electricity, micro-grids	Energy system
Activities disaggregation	User-defined	User-defined	Pre-defined	User-defined	Pre-defined	Pre-defined	User-defined
Time resolution	Medium to long-term, user defined time steps	Medium to long term, user-defined time-step	Short-term, 1 year time period and 1 hour time step	Short-term, 1 year time period and 1 hour time step	Short-term, 1 year time period and 1 hour time step	Short-term, 1 year time period, user defined time step	Medium to long-term (20-50 years), user defined time steps

2.3.2. Building energy modelling: main methodologies

This section describes some of the bottom-up building energy modelling methodologies to assess the current and predicted energy consumption of a buildings stock. In particular, the attention is focused to the ones that might be applied at an urban territorial scale for planning purposes and therefore to the ones coupled with spatial analyses.

Engineering or Building Physics and Statistical methods represent the two methodological groups (Swan and Ugursal, 2009), while the combination of the two methods is referred as hybrid models. (Kavgic et al., 2010; Oladokun and Odesola, 2015; Swan and Ugursal, 2009). The methodological groups are characterized by differences in calculation methodology, time and spatial resolution, disaggregation level of input data and results.

Building physics or **Engineering models** are based on traditional thermodynamic relationships (Aydinalp-Koksal and Ugursal, 2008) and, according to (Swan and Ugursal, 2009) are classified into:

- Archetype: buildings are clustered into representative building classes defined by key building thermo-physical characteristics (Corgnati et al., 2013; Shimoda et al., 2004). Building simulation software is adopted for assessing current and future energy consumption of building archetypes (Ballarini et al., 2014a; Wan and Yik, 2004). One of the main criticalities related to building archetypes is that are very data intensive to be defined and to be representative of a wide set of buildings.
- Sample: surveys and monitoring campaign support the data collection at the base of sample modelling. With this approach, it is possible to model the actual behaviour of the building stock, but limited applications of sample method were found at local level (Cheng and Steemers, 2011).
- Population distribution: used to reflect energy consumption of household appliances regarding the ownership saturation rate of appliances. It is an accounting method mostly adopted for building up the electric distribution load of an area or to estimate the energy consumption of household appliances (Kadian et al., 2007; Saidur et al., 2007).

A literature review was performed to provide an overview of how engineering methods were applied at the urban scale. Among the most relevant applications, Fabbri et al. (2012) studied how the typology factor influence energy saving in heritage buildings. A GIS platform linked different heterogeneous data, among which the building Energy Performance Certificate. The archetype method was applied by Yamaguchi et al. (2007) to evaluate carbon emission reduction scenarios in the commercial sector. A simulation model capable of considering the various parameters affecting energy use and management was developed. Mattinen et al. (2014) presented a GIS-based calculation, based on building archetypes, for estimating energy use and greenhouse gas emissions for the residential building stock. In 2001, Jones et al. (2001) introduced another GIS-based Energy and Environmental Prediction model based which provides additional information to archetypes, based on a "*drive-pass*" survey. Caputo et al. (2013a) and Costa (2012) proposed a methodology in order to evaluate the energy performance of the built environment at the city level. Mastrucci et al. (2013) developed a dynamic thermal simulation and indoor thermal comfort analysis to support sustainable urban planning. Österbring et al. (2016) developed a methodology to integrate energy performance certificates, monitored energy consumption and geometric data derived from a GIS model. A GIS-based simulation model was proposed by Li et al. (2016) in order to assess how building typology and urban morphology influence building energy consumption and CO_2 emissions. Delmastro et al. (2016) developed several long-term scenarios assessing the energy saving potential and the relative cost related to different retrofit measures. Moreover, a socio-economic feasibility of retrofit measures was studied thanks with the support of energy performance certificates and GIS tools.

An alternative to engineering models, **statistical methods** aim to correlate historical data on building energy use/external conditions and buildings characteristics. They are divided into:

- Regression analyses: search for the relationship between energy consumption and its identified relevant drivers (Dascalaki et al., 2010; Fracastoro and Serraino, 2011a; Theodoridou et al., 2011). On the contrary of engineering methods, regression analyses do not require detailed building information, but a high amount of data is needed to develop the model. In some applications, regression methods can be suitable for assessing the retrofit potential of large building stock as proposed by Walter and Sohn (2016).
- Conditional Demand Analysis (CDA): it is based on regression techniques, but suitable for large datasets analysis. Due to the lack of flexibility, the analysis of energy conservation measures on demand variation isn't allowed therefore this method will not be further considered in this thesis.

- Neural network models (NN): investigate the correlation between a wide range of variables and parameters based on a large training dataset. They were largely used for prediction problems at the individual building level, but also at a larger scale (Aydinalp et al., 2004, 2002). NN is suitable for the evaluation of energy consumption and the impact of socio-economic factors (Aydinalp-Koksal and Ugursal, 2008), but they are not suitable for defining energy conservation measures even if some applications exist (Krarti et al., 1998).

Statistical methods were applied at the urban scale in many applications. In particular, Dall'O et al. collected energy audits information and created a comprehensive database with building energy performances (Dall'o' et al., 2012). In the city of Torino, Mutani and Vicentini (2013) applied a regression-based analysis to find the relation between building energy consumption, building compactness and construction period. Other statistical models were applied to the city of New York by Howard et al. with the aim of estimating the building sector energy end-use intensities (Howard et al., 2012).

The different engineering and statistical methods can be combined into **hybrid models** in order to merge their strengths. Hybrid models were applied to a small sample and performed well, but according to Chalal et al. (2016) "*it could be possible to utilize them in urban energy planning when certain parameters, especially the thermal ones, are unattainable*".

Example of a hybrid application is EnerGIS, proposed by Girardin et al. (2010), that support long-term retrofit scenarios analyses defined on the base pinch analysis and statistical methods. In 2013, Ascione et al. (2013) suggested a new method for the calculation of the space heating demand for buildings with the aim at characterizing both winter and summer energy performances. Their target was to promote efficient retrofit solutions for existing buildings and effective design for new ones. The integration of regression and archetype methods was proposed by Mutani and Pairona (2014) to calculate the energy consumption of residential building stock by starting from census information and real energy consumption data.

Figure 2-4 summarizes the characteristics of major approaches. Among the engineering methods, although it might be possible to use the sample and population distribution models at urban level, the most widespread method applicable for urban spatial analyses is the archetype one. This method allows both short and long-term analysis and the possibility to create energy retrofit scenarios. Between the mentioned statistical approaches, the regression methods were utilized in urban applications more than the other methods. This method is appropriate for short-term planning based on large data requirement and to create energy retrofit scenarios. Concluding, the archetype and regression models were the most used modelling techniques to perform spatial urban building energy modelling due to their suitability for energy savings potential assessment.

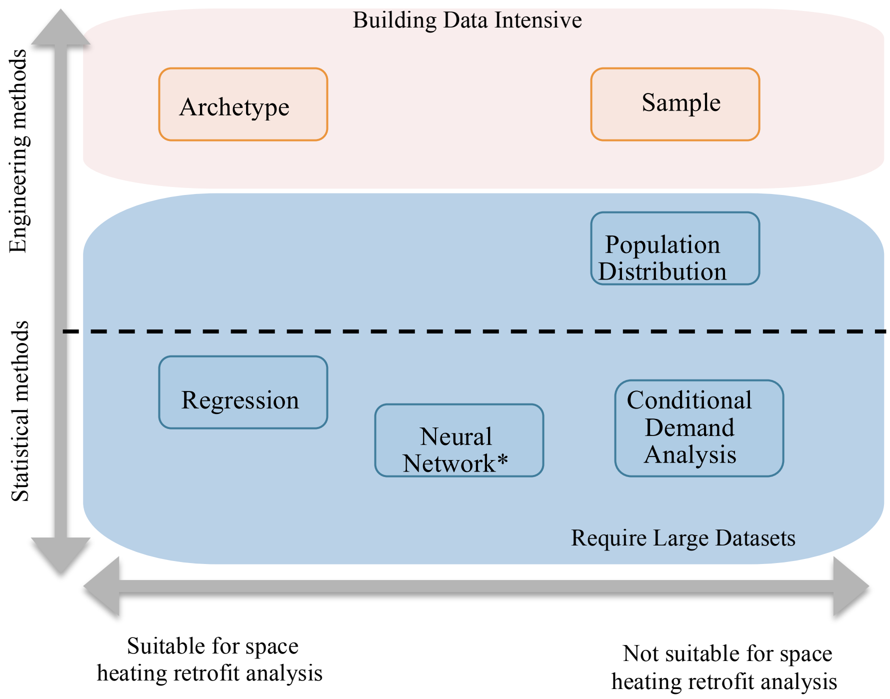


Figure 2-4: Mapping of some major characteristics of building energy modelling techniques. * Not developed with the purpose of retrofit analysis, but some applications exist.

By this literature screening, it emerged the fundamental and strictly necessary role of spatial analyses in urban context. In fact, by using a Geographic Information System (GIS) support it is possible to archive and transfer data and results to a geo-referred database (Delmastro et al., 2016c; Fonseca and Schlueter, 2015) and to set Urban Energy Maps providing an overview of the time evolution of the stock and main results (energetic, economic and environmental); moreover, it aids to easily identify criticalities, to support advanced energy planning and to disseminate the output of the analysis. Furthermore, spatial modelling analyses are useful for allocating different supply side and demand side technologies to the different urban areas according to their energy and social requirements (Jennings et al., 2013).

Chapter 3

Investigation approach

This section presents the methodological framework adopted in this Ph.D. dissertation for Chapter 4, 5 and 6 of the thesis. The organization of these three Chapters relies on the scientific literature screening performed in the previous chapters. The chapters are presented in a narrative way for providing guidelines to be followed during the modelling applications, even when different situations from the presented case study need to be faced. This decision relies on the willingness to contribute in providing a theoretical background to support the development of new methodological combinations in future applications characterized by different objectives and boundaries conditions. The logical connections among chapters and research questions are presented into Figure 3-1. As it can be observed, the starting point of the thesis is the identification, during the explorative sections (Chapter 1 and 2), of major limitations in the field of urban energy planning, which are:

1) The lack of well-recognized procedure and an agreed methodological framework to support urban energy planning: Which are current and future challenges and barriers in long-term urban energy planning? Which can be a theoretical framework to support this practice?
2) The lack of a medium-to-long term planning vision and the habits to focus on single-sector analysis: *How to "adapt" long-term comprehensive energy system methods and tools to urban applications?*
   Which are the strengths, weaknesses and main opportunities of the two main comprehensive energy system method/tool families (simulation and

optimization approaches) in urban applications? How to couple them with building energy modelling?

3) The need of addressing the economic viability and the profitability of the different available heat strategies in district heated cities: Are comprehensive energy system methods and tools suitable to support holistic heat decarbonisation strategies in urban areas (involving building retrofit and new heat generation technologies)?

In order to answer these unresolved research questions, a case study application is proposed for applying different methodologies. The case study is structured according to the Integrated Energy Planning Procedure – Phase I and Phase II proposed by (Mirakyan et al., 2009). These Phases were addressed as real planning applications, standardizing the steps to be followed and the questions to be necessarily answered even if not specifically expected or available for the specific proposed case study. In such way, the thesis may also represent a guideline for future energy planning applications in urban areas.

The preparation phase, proposed in Chapter 4, establishes the ground foundation (preliminary actions) for performing the modelling approaches further proposed in Chapter 5 and 6. The steps of the Preparation phase are common to all planning activities and are subdivided in stakeholder analysis (dos Muchangos et al., 2017), selection of the methodologies according to the planning objectives and data collection. In the modelling chapters, two different comprehensive modelling approaches (Simulation and Optimization) are applied in order to (i) understand how to apply them in the urban contexts; (ii) scrutinize their major strengths and shortcomings according to different planning goals and applications and (iii) understanding heat decarbonisation options in district heated cities. The major methodological solutions and insights may be indirectly derived from the case study, but are further pointed out, generalized and discussed in Chapters 7. The case study-related Chapters are organized into Introduction – to explain the chapter scope and research background -, Methodology – to describe step by step the analytics-, Discussion and Conclusions to sum up the major results.

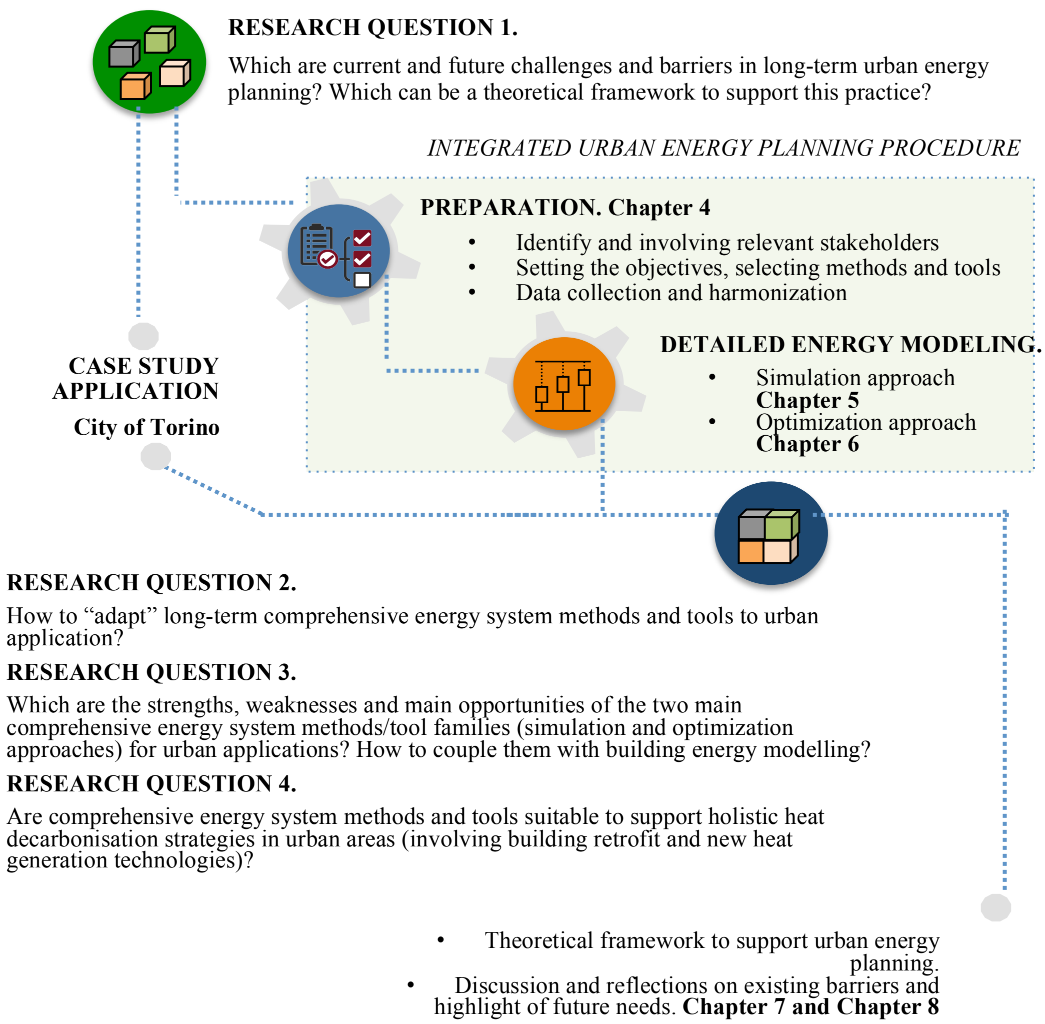


Figure 3-1: Investigation approach.

The proposed research methodology is founded on the fact that integrated urban energy planning has a high degree of complexity, which cannot be managed by a single discipline. It combines energy planning (bottom-up energy system models), building physics (engineering models) and territorial analysis (geographic information systems) to provide an interdisciplinary methodological framework (Figure 3-2). This combination of methodologies allows providing insights with attention to the **technical, financial and environmental dimensions**.

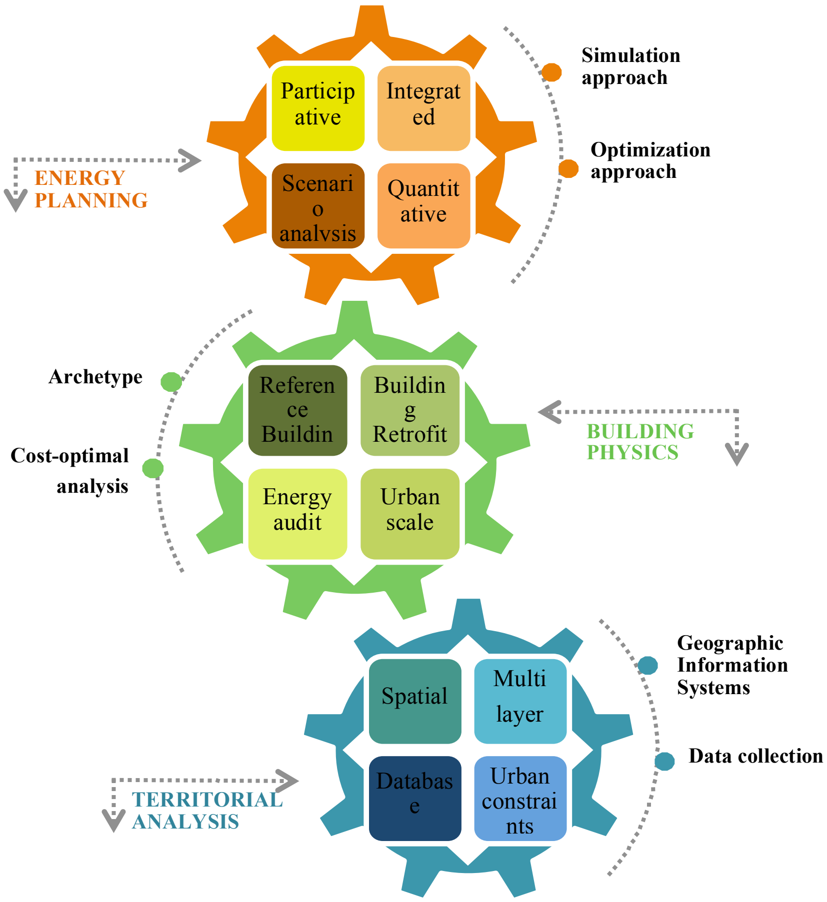


Figure 3-2: Overview of the principal characteristics of the combined methodology.

This interdisciplinary approach allows understanding - and proposing some reflections - the current limitations in urban energy planning practices. The applied methods and tools were selected according to specific criteria introduced in Chapter 4 and according to the conclusions of the literature screening. Data availability didn't influence the choice of the modelling approaches, but impacted on their structure and consequently on the results.

Even if applied to the same case study city of Torino, the simulation and optimization approaches were applied assuming different boundaries conditions:

- The simulation approach proposed in Chapter 5 analyses space heating only and considers an area occupied by 100 Mm^3 of buildings and the generated scenarios involve building renovation and new district heating investments in that area. The proposed scenarios were developed specifically focusing on retrofit options and new district heating solutions, maintaining all the rest of buildings heated by individual gas boilers. This choice is justified to keep the scenarios description simple and easy to understand, but the framework allows to further introduce other distributed generation options;

- The optimization approach further extends the analysis to the whole urban area and it includes 5 energy services (space heating, water heating, lighting, space cooling and other electric uses). In this case, new technologies for every end-use service are taken into account.

The presentation of the two approaches in this way has the additional purpose to show the differences between a home-built model and the adoption of a model generator. From Chapter 5 to Chapter 6 a broader decarbonization view is provided, taking into account all building energy services including the electricity-related ones.

The final outcome of this thesis is represented by a contribution in the development of standardized theoretical-methodological framework/guideline that may enrich future urban energy planning applications. Research outcomes that were previously published by the author were used to support the main conclusions of the thesis and are listed at the end of thesis in Annex A. The specific contribution of the author in every paper is listed in Annex A as well.

Chapter 4

Preparation and Orientation Phase

4.1 Overview

The Preparation and Orientation Phase includes all the preliminary actions for creating a well-structured planning framework in order to proceed with the next phases of the energy planning procedure (Mirakyan and De Guio, 2013). Among the possible actions of this phase, the most relevant ones are referred to definition of the objectives, stakeholders' involvement and data collection (Figure 4-1).

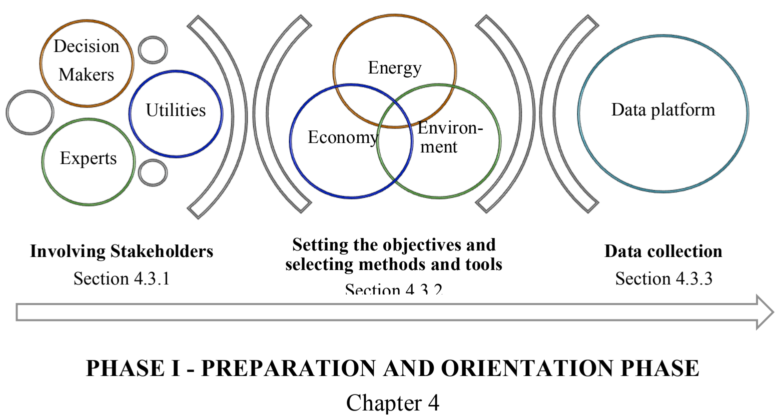


Figure 4-1: Main actions of the preparation and orientation phase.

Key findings:

Methodology:

- High demand disaggregation levels are required for urban energy planning: methods/tools should be flexible;
- Comprehensive energy system models/ tools are suitable for integrated energy planning: multi-commodities, multi-sectors, focus on environment, energy and economy;
- None of the reviewed comprehensive energy system *simulation* tools guarantee the required level of demand disaggregation: a specific model will be developed; while among comprehensive energy system *optimization* tools, the TIMES model generator was selected;
- Involving urban stakeholders enriches the definition of energy planning goals, facilitates the understanding of urban needs and data collection;
- The data collection process is very challenging: GIS tools help in calculating territorial data and harmonizing data from different sources.

Case study:

- Torino energy planning history followed a standard procedure: it is not familiar with long-term integrated energy planning;
- Involving stakeholders was very challenging: a participative energy planning approach is not common practice;
- Many data are still not available or difficult to access with long bureaucratic waiting time;
- The Torino building stock was fully characterized: most of the buildings pre-dates the energy regulations, leading building retrofit to be a hot planning topic;
- Torino is a district-heated city with buildings in compelling need of retrofit: the planning objective was set as understanding the long-term (2050) system dependency of energy savings derived from building retrofit.

Key limitations:

- Stakeholders weren't actively involved in the planning process, but individually contacted for sharing the planning objectives and supporting data collection;
- Lack of high quality data or updated data related to the urban energy balance and to the technology mix share.

Declarations.

Part of the work described in this Chapter was also previously published in the following publications, further reported in Appendix A of this thesis.

- Torabi Moghadam S., Delmastro C., Corgnati S. P., Lombardi P. (2017). Journal of Cleaner Production, 165, pp. 811-827.
- Delmastro C., Mutani G., Corgnati S.P. (2016). Energy Policy, 99, pp.42-56.
- Mutani G., Delmastro C., Gargiulo G., Corgnati S.P. (2016). Energy Procedia, 101, pp.384-391.

The adopted building volumes were derived from the work of (Mutani and Pairona, 2014).

4.2 Introduction

The Preparation and Orientation phase represents a fundamental preliminary step in urban energy planning by setting the bases of the whole planning procedure (Mirakyan and De Guio, 2013). In this phase, the planning working group is created for setting the city objectives and collecting all the relevant data. Some of the questions to be answered in this phase are related to the identification of urgent community problems, the city short and long-term objectives, the relevant stakeholders, the geographical boundaries, the technologies that may be adopted, the existing projects and the economic resources (Steidle et al., 2000). The activities of this phase are strongly related to the specific local conditions, the data availability and the experience of the city in energy planning. Therefore, the way this phase is performed cannot be systematic and generalized for every reality and may encounter several problems; it is important to stress that the crucial common part is related to the understanding of the current energy and environment situation in order to identify urban priority needs according to the available budget. Some problems that should be avoided in this phase was identified in (Mirakyan and Guio, 2014) among which the most relevant are: cooperation difficulties and conflicting objectives among urban organizations, the presence of specific expertise creating barriers to innovative solutions and fossilize on existing planning traditions.

In this thesis, the city of Torino was selected as a case study. A brief introduction to the city context is presented in Section 4.3 while the actions undertaken for the case study are described in Section 4.4 and discussed in Section 4.5.

4.3 The case study: background information

Background information is related to the useful indicators for understanding the city context and for identifying the principal drivers of energy use. It is related to buildings (residential and non-residential), transport (freights and passengers), heat and power, industry, water treatment, waste treatment and agriculture. Due to the purpose of the thesis, the case study focuses on buildings and heat and power. As indicated in (International Energy Agency, 2016), the key factors affecting an urban energy system are: affluence (GDP/capita), density (number of people per square kilometre), building stock and infrastructure age, land availability, economic structure and climate. These key factors, which are deepened and specifically adapted to the methodology in further sections, are related to (International Energy Agency, 2016):

1) Socio-demographic situation: building occupation, culture tradition, building occupancy and composition, social and economic structure;

2) Geophysical environment: climate, location-related boundaries, resource availability;
3) Built infrastructure: energy and transport networks and infrastructure, building density and design;
4) Institutional context: urban governance.

This section provides a general overview of the case study city of Torino to understand the city context and main characteristics.

Torino is the capital city of the Piedmont Region (Northeast part of Italy). It is sited in a continental climatic zone (2617 Heating Degree Days at 20°C) and occupies an area of roughly 130 km^2. In 1991 the population was 979,839 inhabitants and was progressively reduced – mostly moved to adjacent municipalities - until 2002, accounting for approximately 896,818 inhabitants. Over the following years, the population slightly increased thanks to a higher number of foreigner citizens and reached 899,455 in 2014. This economic, urban and cultural transformation was mostly driven by the decentralization of automotive production in other areas. As a consequence, some workers' urban areas were abandoned leading the city to promote an urban renewal by reconverting urban infrastructures and part of districts. In 2006, the city hosted the Winter Olympics, and for this event, it promoted urban renovation actions that brought Torino to the current condition (e.g. the recovery of historical heritage and the improvement of transport infrastructures).

Together with urban renovation, the city of Torino was involved in many energy-related projects and initiatives. Indeed, the Municipality joined the Covenant of Mayor Initiative in 2009. In this framework, the first energy plan of the city "Torino Energy Action Plan –TAPE (Città di Torino, 2012)" was developed. In the TAPE, the energy balance of the city in 1990 and in 2005 was evaluated and the related emissions were accounted. The action plan has the main objective to identify measures for reducing the urban carbon emissions of 40% to 2020 (with respect to 1990 levels). As shown in Table 4-1, the energy consumption in 2005 was accounted roughly 16,300 GWh/y with related carbon emissions of 5,100 kt_{CO2}/y. According to the energy balance, 56% of total CO_2 emissions were related to the built environment, 30% to industry and 14% to mobility. Therefore, the built environment represents a key consumption and CO_2 emissions voice taking into account that more than 80% of buildings pre-dates the energy regulation law (around 1980). This also justifies the specific interest of Torino in understanding the building energy retrofit potential and studying alternative energy sources. Being this 2005 energy balance the unique official reference of top-down data, it will be used as major reference in this thesis.

Table 4-1. 2005 energy consumption and CO_2 emissions data for the city of Torino (Città di Torino, 2012).

	Energy consumption (GWh/y)			CO_2 emissions	
	Electricity	**Fossil Fuels**	**Total**	**kt/y**	**%**
Built environment	2,682	8,463	11,145	2,857	56%
Municipal buildings	61.5	313	374.5	70	1%
Service buildings	1,442	1,303	2,745	997.1	20%
Residential buildings	1,093	6,847	7,940	1,744.8	34%
Public Lighting	86.8	/	86.8	44.8	1%
Industry	1,631	3,208	4,839	1,509	30%
Transportation	28.6	287.5	316.1	735	14%
TOTAL	4,342	11,958	16,301	5,100.3	

The Municipality of Torino also joined the European Innovation Partnership "Smart City & Communities" (European Commission, 2011b) launched in 2011 by the European Community. In this context, the Municipality declared his intention in becoming a Smart City. The commitment is confirmed by participating to the Smart City National Observatory developed by the National Association of Italian Municipalities (ANCI, 2017). In 2013, the Municipality, together with the Torino Smart City Foundation (Torino Smart City Foundation, 2018) and Torino Wireless (Torino Wireless, 2018), developed a Smart City Master Plan "SMILE - Smart Mobility, Inclusion, Life&Health, Energy". This plan identified a set of actions for every SMILE dimension for supporting the development of a local strategy both in short and in medium-long term and re-launching itself. The core objectives that Torino pursues as Smart City are: (i). to provide more efficient services to citizens (simplified and digitized services supported by new skills and work processes); (ii). to promote industrial development and economic growth of the ecosystem (start-ups, new business model); (iii). to encourage citizens participation and a more inclusive society (promoting information, dialogue and bottom-up approach, both online and offline); (iv). **to support innovative solutions for balancing citizens' lifestyle and the impact it has on the environment and for protecting common goods**; (v). to re-think the use of public transport and soft mobility; (vi). to improve the urban environmental conditions. Together with supporting the strategy beyond the emission reduction objective, this thesis is particularly focused on addressing point (iv) of the Smart City objectives.

The described strong commitment of the Municipality allowed reaching some achievements regarding citizens' services and urban life quality. The Smart City activities of the city were ranked according to two Italian protocols: the ICity rate (15 sustainability dimensions represented by 113 indicators, (FPA srl, 2017)) and the Smart City Index (6 sustainability dimensions represented by 18 indicators, (Easy Park Group, 2017)). In the ICity rate, the city of Torino was ranked as 7^{th} over 106 Italian cities while in the Smart City Index Torino is in 69^{th} position over 100 cities. Furthermore, in 2016 Torino won the second prize in the "European Capital of Innovation" contest, awarded by the European Commission. An overview of some of the major indicators for the city is listed in Table 4-2. By looking at the ranking results and these indicators of the city against the national (average) values, it is possible to get first general insights on the "good" and "bad" performances, and hints for future area of improvement. Critical points of the city include: high levels of particulate concentration, low tourism, free wi-fi areas and digitalization. As major strengths of the city can instead be highlighted: mobility planning, little accidents, wastewater treatments, evictions, early leavers, waste management, open data, innovation, high efficiency of the courts, voluntary homicides, and shared administration.

Table 4-2. Indicators of the city of Torino (ISTAT, 2015) . * data at Province level

Indicator	Year	Unit	Torino	Italy
Available income per capita	2012	Euro (€)	20,455*	17,307
Employment rate	2013	Per 100 person (age-range 20-64)	65.9*	59.8
Specialization in knowledge-intensive productive sectors	2011	Per 100 employees	10.7	4.4
Families with broadband Internet connection	2011	Per 100 households	46.4	44.9
Losses of the pipe network for distribution of water to the consumers	2012	water lost on the volume of water introduced (%)	36.9	37.4
Urban air quality	2013	Exceedance of daily	126	n.a.

		limit PM10 (days)		
Noise pollution	2013	Noise controls limit exceedance (100,000 inhabitants)	4.1	4.4
Urban green space availability	2013	m^2 per inhabitant	24.1	32.2
Total density of green areas	2013	Fraction of the municipal surface	19.8	18.2
Urban vegetable gardens	2013	m^2 per 100 inhabitants	220.7	18.4
District heating	2012	m^3 per inhabitant	58.3	10.8
Cars lower than Euro 4 class	2013	Per 1000 inhabitants	393.9	311.8
Urban waste sent to landfill	2013	% of total municipal waste	58.5 *	36.9
Separate collection of urban waste	2013	% of total municipal waste	51.0 *	42.3
Time dedicated to mobility	2011	Minutes (average)	26.9	23.4
Density of urban networks of Local Public Transport	2012	Seats-km per inhabitant	7144.8	4794.0
Density of cycle paths	2013	Per 100 km^2 of municipal area	137.4	18.9
Availability of pedestrian areas	2012	m^2 per 100 inhabitant	45.8	33.4

As can be derived from this brief introduction of the case study, the approach to the “smart city” and more in general to energy planning in Torino has followed a standard path: the preparation of the Sustainable Energy Action Plan (SEAP- TAPE), the participation to EU initiatives, etc. and quite standard (top-down) approaches (definitions of high-level targets and target-oriented analyses) and priorities (GHG reduction, renewables) on the example of national and supranational entities. It can be concluded that the activities were strongly coordinated by the Municipality, contacting stakeholders when needed, and by following a traditional sectorial approach. **One of the goals of this thesis is to critically test an integrated and comprehensive cross-sectoral approach to support the definition of long-term energy plans starting from the bottom (real needs of the city).**

4.4 Methodology

The preparation and orientation phase is performed using three steps: stakeholders' identification, setting the objectives, selecting methods and tools and data collection. The goal of this Phase is to build a solid base for starting quantitative modelling analysis, having clear in mind the city major criticalities, the goal of the energy plan, the system limits and possible scenarios and measures to be taken into account. The methodology adopted for this phase mostly refers to (Mirakyan and Guio, 2014) and to (Steidle et al., 2000). This section briefly presents the major interesting actions to be implemented and the associated theoretical concepts.

4.4.1 Identifying and involving relevant stakeholders

Engaging principal urban actors is very important for developing a shared urban vision, collecting the available data and proposing an agreed final objective for the city (Bottero et al., 2015; Linnenluecke et al., 2016). The first step is represented by the stakeholders' analysis to identify the key stakeholders and their "interests" and "power" in the area. In fact, a key question is whom to consider as a stakeholder: urban stakeholders may be representative of the municipality or other public institutions/authorities, government, developers, industrial unions, commercial companies, energy service companies or utilities, NGOs, health and environmental associations, citizens etc. Stakeholder analysis and social network analysis are widely used in social science, public management and planning analyses. The identification of stakeholders can be done with purely theory methods (dos Muchangos et al., 2017; Li et al., 2017) or together with planning customers through semi-structured interviews or other methods as in (Hein et al., 2017). Once the stakeholders are selected, they should be involved in the planning process. This can be done in possible participative ways such as group facilitation methods, interactive group process, workshop and focus group organization (Cajot et al., 2017).

Nevertheless, this thesis is an energy planning exercise; therefore a workshop dedicated to the thesis and involving all the stakeholders wasn't organized. The most relevant stakeholders, identified as the Municipality, the district heating utility company and the Consorzio per il Sistema Informativo (Consortium for the Information System, CSI) were contacted individually. In this thesis, input from the selected stakeholders mostly refers to data collection, being aware that in real applications all the assumptions should be defined with all the involved stakeholders. According to (Steidle et al., 2000), the questions to be answered together with the stakeholders are:

- *Which are the urgent criticalities of the community?* As summarized in Section 4.3, in the smart city context, the main critical issues are related to local pollution, tourism and digitalization. In the TAPE energy action plan, the built environment was identified as responsible for 56% of urban CO_2 emissions. These leads mobility and buildings to be the prioritized sectors for energy planning. In this thesis, the building stock is the focus of the research in terms of both demand and supply options.
- *Which are the short and long-term urban objectives?* As explained in Section 4.3, the TAPE goal is to reduce urban carbon emissions by 40% compared to 1990 levels. Any long-term quantitative objectives and targets were set for the city; therefore, in this thesis, several decarbonization targets to 2030 and 2050 are proposed, with the goal of improving environmental sustainability and economic competitiveness.
- *Which are the major drivers of the energy demand?* Focusing on the building stock, major drivers are represented by population and built floor area or heated volume. In this application, the heated volume was considered the main driver of space heating consumption, instead of floor area, since different building heights were associated with the different construction periods. Furthermore, for non-residential buildings, the heights may considerably vary among building classes leading building volume to be a more significant driver. As previously explained, the city experienced a decrease in the population followed by a slight increase of foreign citizens. In this thesis, several evolutions of these drivers were not taken into account, leaving open the possibility of generating further scenarios in future exercises.
- *Which are the considered boundaries of the city for urban energy planning purposes?* In this thesis, the considered urban boundaries refer to the geographic-plus definition of (Keirstead et al., 2012) as defined in Section 2.2.
- *Which technological solutions should be taken into account?* One city goal is to support innovative solutions for balancing citizens' lifestyle and the impact it has on the environment and for protecting common goods. Taking into account this objective and the focus on the building stock, in this thesis main alternative possible solutions involve new heat and power generation options (e.g., change of fuel mix) and building retrofit options (e.g., envelope improvement).
- *Which are the already existing activities and projects related to urban energy planning? Which have been the previous actions related to energy planning?* As previously affirmed, the city launched many initiatives in the energy and

smart city field. In particular, some important projects for this thesis are related to: the creation of an online platform called Geoportale (Città di Torino, 2017) in which it is possible to visualize urban maps and to download geo-referenced data related to the statistical census (e.g. population, occupied buildings) and to urban parameter (e.g. streets network, school locations); the Cities on Power project (Central Europe, 2017) with the goal of promoting the use of renewable energy in urban areas. In particular, in this framework, Torino developed a platform showing the available rooftop surface for exploiting solar technologies and estimated thermal energy consumption of residential buildings. Another relevant initiative, as previously affirmed, is the TAPE, providing an official urban energy balance and a set of solutions to be implemented before 2020. Among the most relevant, the proposed TAPE actions from 2010 to 2020 include the energy retrofit of Municipal buildings (-1.75 kt_{CO2}/y from 2010 to 2013) and of residential buildings (-103 kt_{CO2}/y at the regional level from 2010 to 2016), the installation of PV panels on Municipal building rooftops (-619 t_{CO2}/y from 2010 to 2015), energy production from renewable energy sources (-31.7 kt_{CO2}/y from 2007 to 2020), increasing the district-heated volume of roughly 4Mm^3 (-4.4 kt_{CO2}/y from 2009 to 2020), substitution of inefficient individual boilers (-40 kt_{CO2}/y at the regional level from 2009 to 2020), substitution of inefficient lamp bulbs (-4 kt_{CO2}/y from 2009 to 2020) and LED usage in traffic lights (-8.6 kt_{CO2}/y from 2009 to 2020), the retrofit of public transport vehicles (-13.5 kt_{CO2}/y from 2009 to 2020), increasing the use of bicycles in urban areas (-22 kt_{CO2}/y from 2009 to 2020) and increasing the electricity production from urban solid wasted (-165 kt_{CO2}/y from 2009 to 2020).

- *Which may be the long-term benefits of the energy plan?* The long-term benefits should be related to improved citizen life quality and energy services by enhancing energy efficiency, guarantee higher comfort at home and exploit local resources.

In addition, other proposed questions not considered in this thesis are: *Who has the responsibility for the defined actions? Which are the available economic resources?*

Engaging all urban stakeholders allows having a broader and more precise vision of which may be the priorities and targets to focus during the energy planning procedure, that in this thesis was identified as the building stock and its decarbonization. As it will be discussed in Section 4.5, even if the direct and participative involvement of all urban stakeholders was impossible at this stage, two workshops involving many relevant local actors –not directly related to the Torino case study- were organized to identify the priorities for local energy planning, providing a strong support to this thesis.

4.4.2 Setting the objectives, selecting methods and tools

The definition of the planning objectives is a fundamental step for the whole planning process, influencing the choice of the energy system boundaries, the selection of the methodology and the whole scenarios analysis.

In general, this step is consequential and complementary to the selection of stakeholders. It requires the organization of workshops or meetings to start the real planning process and the definition of common objectives. Together with the identified stakeholders, the questions listed in section 4.4.1 should be answered in order to raise the awareness of current problems and open questions, to define the final goal or objective of the energy plan, the time horizon of the analysis and the available time to perform the plan. In real applications, the economic and the planning management structure and responsibility should be defined in this step. Defining the planning objectives is strongly related to the understanding of the urban needs, to the reception of national or supranational policies, energy trends and technology deployment. This action requires an in-depth analysis of the present and historical situation, an investigation of possible strategies, plans or programs, identify urban barriers and some possible available solutions.

According to major research issues presented in the Introduction and taking into account that Torino is a district heated city with low performing buildings, the energy planning objective is defined **as understanding the long-term (2050) system dependency of energy savings derived from building retrofit in district heated realities**. These analyses involve two of the most important options for decarbonization: the reduction of building energy demand and the improvement of heat generation efficiencies. These two measures are strongly related to an energy system vision: variation in thermal demand will occur as building energy efficiency improves over time. Particularly in district-heated cities, the variation of thermal demand will impact the operation and generation strategies of the district heating system and could influence any new investment strategies. As explicatively shown in Figure 4-2, new investments in the heat supply mix may shift the merit order curve and reduce the heat production cost, but at the same time a thermal demand reduction may impact on the operation/dismissing of existing baseload plants (a minimum operation should be guaranteed for CHP as an example). Finding synergies between energy efficiency strategies in building renovation and district heating supply is therefore fundamental for the success of urban heat strategies and for avoiding unnecessary investments.

Stated the planning and research goal, the methodology and/or tools to be adopted should be selected and defined. In this thesis, the methodologies were chosen according to the nature of the planning goal, while data availability impacted on the modelling structure only. To catch demand-supply side interactions in the planning process, an energy system comprehensive approach is required. In addition, to deal with infrastructure evolution, a long-term approach is necessary. Moreover, the specific focus on urban areas and demand aspects **highlights need of high level of disaggregation of the demand for local application**. This, with respect to traditional planning applications, **requires a combination of different methods and tools and the selected ones to be extremely flexible**. As specified in Section 3, both simulation and optimization methods for generating explorative and normative scenarios will be tested in this thesis. Among these, a wide overview of existing comprehensive energy planning methods and tools is provided in Section 2.3.

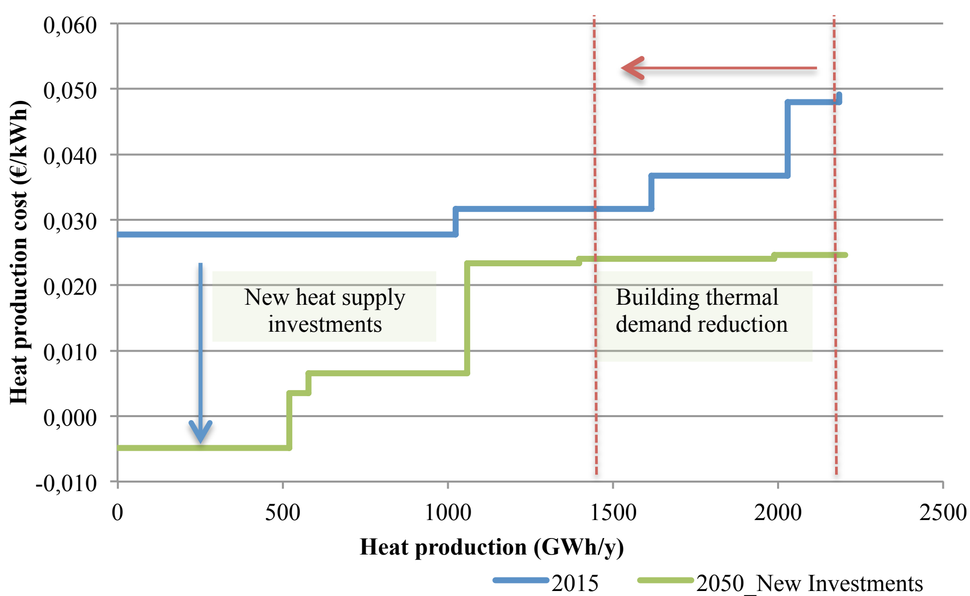


Figure 4-2: Example of the effects of new heat supply investments and demand reduction on the heat production cost.

Among the proposed methods, the criteria that supported the selection were:

(i). Time horizon: medium/long-term time horizon;

(ii). Time resolution: low resolution may be fine, taking into account that the focus is on thermal energy consumption. However, it should be detailed enough to avoid an unacceptable overestimation or underestimation of renewable energy sources production/consumption;

(iii). Flexibility in building the model: a high level of flexibility is required for structuring the models, in particular for modelling both demand supply side and guarantying a high disaggregation level of the demand;

(iv). Possibility to soft- or hard- linking with spatial tools: essential role of spatial analysis in local applications;

(v). Possibility to perform energy, environmental and financial evaluations: energy planning should not neglect these three dimensions of sustainability.

For simulation purposes, none of the existing tools was deemed suitable to meet all the criteria, in particular none of the reviewed simulation tools allows to deeply disaggregate the demand and to represent heat generation unit with the necessary level of detail or wasn't suitable for the definition of long-term analyses; therefore a specific model was developed (Chapter 5). For optimization purposes, the TIMES model generator was selected for building the modelling framework due to its flexibility and modularity (Chapter 6). Compared to other similar tools based on linear programming (e.g., Osemosys), TIMES was preferred because of its powerfulness, reliability and longer presence in the energy planning scientific community.

Concerning building energy modelling, the principal task is to select a method able to statistically represent the impact of several retrofit measures at the stock level. Taking into account the review performed in Chapter 2, the archetype method is consequently proposed.

4.4.3 Data collection and harmonization

Data collection is crucial for the definition of the modelling structure and the subsequent robustness of the results. A high data disaggregation may represent wider possibilities of investigations, simultaneously very detailed data collection may be challenging and time-consuming (Kelly, 2011). The characterization of the urban energy system requires a large amount of data to be collected, managed and elaborated that might be not always available, requiring the definition of several assumptions or the simplification of the modelling structure. In this thesis, the Reference Energy System (RES) approach, as described in Section 2.2, is adopted for the description of the energy system. The required data to describe an urban RES can be found in different heterogeneous forms: historical time series (typically energy consumption and demand data), geographic data (geometric data and some attributes related to the object) and tabular data (costs etc.). In addition, they can be derived from multiple sources: municipalities, energy utilities, market analyses, statistic institutions, government bodies, academia etc.

The required data to define an urban Reference Energy System are related to both top-down and bottom-up data, both associated with the existing situation and to potential future scenarios:

- Building stock information:
    - Socio-economic, demographic, and building data (e.g., population and prevailing buildings age);
    - Building stock geometrical, typological information (e.g., base surface and height, construction materials, destination use);
    - Available real energy consumption data for a building stock (e.g., space heating energy consumption for sample buildings).
- Technology and energy mix information:
    - Energy balance of the city;
    - Availability of local energy resources;
    - Technological share per destination use and per fuel type;
    - Technology and energy networks parameters (e.g., efficiency, life, losses).
- Economic parameters:
    - Energy prices of commodities;
    - Investments, operation and maintenance costs (variable and fix costs);
    - Existing taxes, financial subsidies etc.
- Territorial parameters:
    - Urban physical constraints for district heating expansion (e.g., historical heritage, rivers etc.);
    - Land occupation plans and city expansion plans;
    - Available space for the installation of new technologies (e.g., rooftop availability for solar technologies etc.).

In this thesis, the structure of models was defined according to the data that are available and accessible, but also including the future possibility to insert data that currently exist, but not accessible today. Some of the data can be asked to the stakeholders (e.g., energy balance, energy consumption etc.) while others need to be specifically calculated (e.g., using spatial tools). Therefore, the data collection process can be divided into (i) Geo-referenced data collection; (ii) Non geo-referenced data collection. The idea in this thesis is to create a geo-referenced platform in which several layers are overlapping and all the data can be stored and managed directly from this database (Figure 4-3). Indeed, in the preparation and orientation phase, the use of GIS is extremely useful to calculated territorial data (e.g., building geometry), to store, manage, visualize and harmonize a vast number of spatial data for urban planning purposes. Through the representation of multiple layers, city development can be represented, where each item is associated with a geometric entity in a proper system of coordinates (Torabi Moghadam, Delmastro et al., 2017). Consequently, a GIS-based supportive database also aids the stakeholders to visualize the current urban situation and therefore to reshape the sustainable objectives.

In order to avoid repetitions among the chapters, in this Section, the data gathering process is comprehensively explained for the collection of building stock information while all the other data voices will be investigated during the Detailed Energy Modelling phase and just briefly introduced here. The energy-related data collection and their elaboration are described in further sections, but a brief overview of data sources is provided even in this section. The buildings thermo-physical characterization derives from previous literature data (EU TABULA Project, 2012) and past as well existing regulation (UNI TS 11300; UNI/TR 11552). Real space heating energy consumption data of residential building samples as well as district heating generation mix and operation schedules were provided the local utility company (Gruppo IREN, 2015) while top-down data related to the urban energy balance refers to the TAPE 2005 data (Città di Torino, 2012). Unfortunately, due to bureaucracy constraints, stakeholders did not provide data related to the technology share that therefore totally refers to existing statistics, literature and author assumptions. Similar approaches were applied to the research of economic and technical information related to existing and new technologies. Table 4-3 summarises the principal data that need to be collected for the definition of an urban RES, explaining which might be the possible data sources, which can be the improvement of data collection when digitalization and smart meters will be further spread, which are possible insights for decision-makers and which data need to be prioritize to support the energy planning community. Some proposals will face the problems of privacy and commercial sensitivity of data that might limit their accessibility even when available. These aspects as well as other data implications will be further discussed in Chapter 7.

Table 4-3. List of data to be collected

Data category & sub-category	Required information	Function	Availability, accessibility	Future enhancement through digitalization & smart meters	Issues to be highlighted to stakeholders	To be prioritized
Building stock data						
Socio-economic and demographic	People age, education level, building occupation rate, rent/propriety, family number etc.	Identification of socially critical areas, support to the estimation of electrical appliances demand, support to spatial disaggregation of results etc.	Statistical data collected during the census at the building level, accessible at the census section level	More frequent update of the data (now every 10 years)		
Stock information	Volume, number of floors, building high, building construction period, destination use etc.	Identification of building archetype, know-how on distribution of buildings volumes	From census data: construction period at the census section level. Thermo-physical characteristics assumed from construction periods, building standards and regulations From GIS and technical offices of the municipality: basic cartography	Possibility to add information about micro-climate, shadings, etc.	Non-residential buildings are scarcely described, requiring ad-hoc specific information	Yes, in particular for non-residential buildings (at the local level)
Energy requirements	Energy service demands per unit of driver (e.g. space heating/volume; water heating/cap; etc.)	Estimation of the energy demand for the different building energy services per building archetype	From building simulation, provided by energy service companies or monitored	Real data with high time resolution through smart meters	Energy performance certificates are useful to understand the building already retrofitted; agreements on data usage can help data exchange	
Data category &	Required	Function	Availability,	Future enhancement	Issues to be highlighted to	To be

sub-category	information		accessibility	through digitalization & smart meters	stakeholders	prioritized
Energy mix & technologies						
Energy balance	Urban energy consumption per fuel type and destination use	Top-down data to calibrate bottom-up analyses, full understanding of the city energy consumption	From the municipality	More frequent update of the urban energy balance (now dated 2005)	The definition of data protocol to be shared with stakeholders may support updating the energy balance	Yes (at the local level)
Technological share	Installed capacity by the different technology per fuel type	Definition of the urban technology mix	From energy utilities, energy balance and municipal/regional cadastre In the thesis: available only for district heating (from local utility) and derived from statistics and the old energy balance	Collection of data to build and update a cadastre	The definition of rules to access the cadastre with privacy attention and pre-defined level of aggregation for the data visualization may help in improving data accessibility	Yes, in an aggregated format (at the local level)
Technology and networks parameters	Efficiency, capacity factor, life, losses, etc. (per size and during the time-horizon)	Estimation of energy consumption per technology and fuel type to match the demand	From academia, research institutions, etc. or from real plants operation	Better technological characterization through monitored data (even of innovative solutions) with detailed technology performances according to climate, operating conditions, technology size, etc.	Increasing the availability of “Reference” database with data to be used by modellers and planners may enhance the transparency of energy planning models and the consequent credibility of results	Yes, (at the global level)
Data category & sub-category	Required information	Function	Availability, accessibility	Future enhancement through digitalization & smart meters	Issues to be highlighted to stakeholders	To be prioritized

Availability of local energy resources	Renewable energy sources potential (solar, biomass, etc.), solar irradiance during the year, waste production, etc.	Definition of constraints about resource exploitation and use	From research, own calculations, municipal offices, public institutions etc.	Real data with high time resolution through smart meters, profile availability, etc.	The availability of these information are crucial for a correct energy planning	
Economic parameters						
Energy prices of commodities	Unit cost of energy sources (produced and imported, current and projections)	Useful to evaluate the total system costs (scenarios can be done on these parameters)	From national regulation authorities for energy, projections from international institutions, academia, etc.			
Technology-related costs	Investment cost for technologies (current and projected), fix and variable operating costs	Useful to evaluate the total system costs (scenarios can be done on these parameters)	From academia, research institutions, etc. or from developer		Increasing the availability of "Reference" database with data to be used by modellers and planners may enhance the transparency of energy planning models and the consequent credibility of results	Yes, (at the global level)
Policy variables	Existing taxes, financial subsidies, etc.	Useful to evaluate the total system costs (scenarios can be done on these parameters)	From governments, or own assumptions to build scenarios			
Data category & sub-category	Required information	Function	Availability, accessibility	Future enhancement through digitalization & smart meters	Issues to be highlighted to stakeholders	To be prioritized

Territorial parameters			
Urban physical-cultural constraints	Presence of historical heritage, rivers, roof-top availability, available land-use, train lines, etc.	Useful to set constraints	From GIS evaluations, from the municipality, surveys etc.
City master plan	City evolution plans	Useful to set constraints, to set the evolution of building volumes etc.,	From the municipality

Starting from the collection of **building stock information**, some relevant literature examples in the field of urban energy planning are (Caputo et al., 2013) and (Tornberg and Thuvander, 2005). In Torino, similar examples that were used as a strong base in this thesis are the works of (Mutani and Vicentini, 2015) and (Mutani and Pariona, 2014) in which the surface to volume ration (index of building compactness) was calculated for every building. In this thesis, a bottom-up approach was adopted and an open source GIS tool (QGIS) was used for the creation of the database. In particular, the tool was used for the identification and quantification of Reference Buildings RB (as defined in section 2.2) and in (Corgnati et al., 2013).

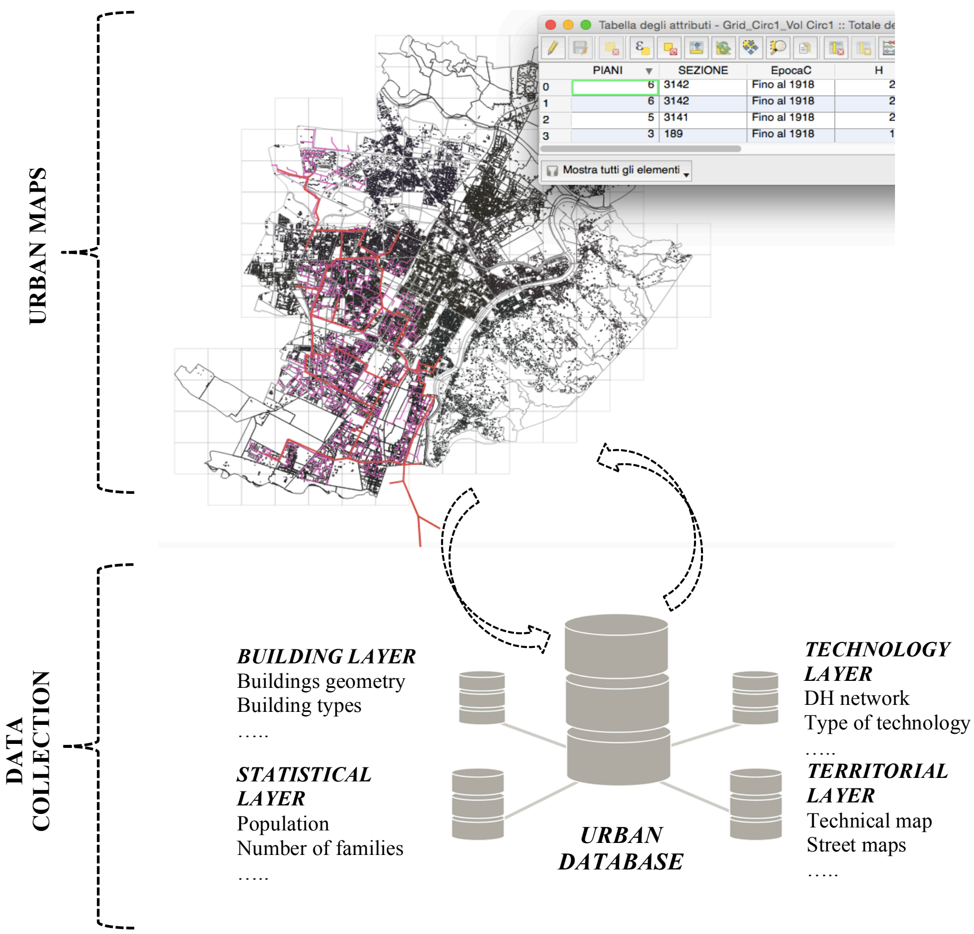


Figure 4-3: Conceptual scheme of the data collection process.

A correct identification of RBs is crucial for modelling the building energy system at the urban scale, allowing to realistically representing the whole stock in terms of buildings construction characteristics (and consequently, also energetic characteristics). The objective of this part of the data collection process is to: (i).

Quantify the spatial distribution of the heated volume of the RBs across the city and (ii). Associate to all the buildings the statically available socio-economic census variables. In this process, statistical data are available at the census tract level (census data, ISTAT) while geometrical data are available at the single building level (Municipality technical map). From the Municipal technical map, it is possible to extract data relative to the building distribution, their destination use, number of floors and their base surface while at the census tract level it is possible to extract information about the construction period, the population and its socio-demographic conditions. The first step of consists in matching these two layers as in Figure 4-4. In addition to the identification of RB, this step allows knowing the real volume of occupied buildings sited in each census section. As a result, 62,643 occupied buildings were accounted in the city. The building stock occupies approximately 202 Mm^3 volume, of which almost 82% is residential and 18% non-residential. The average surface of residential apartments is equal to 75.3 m^2 with a floor height of 3.5 m.

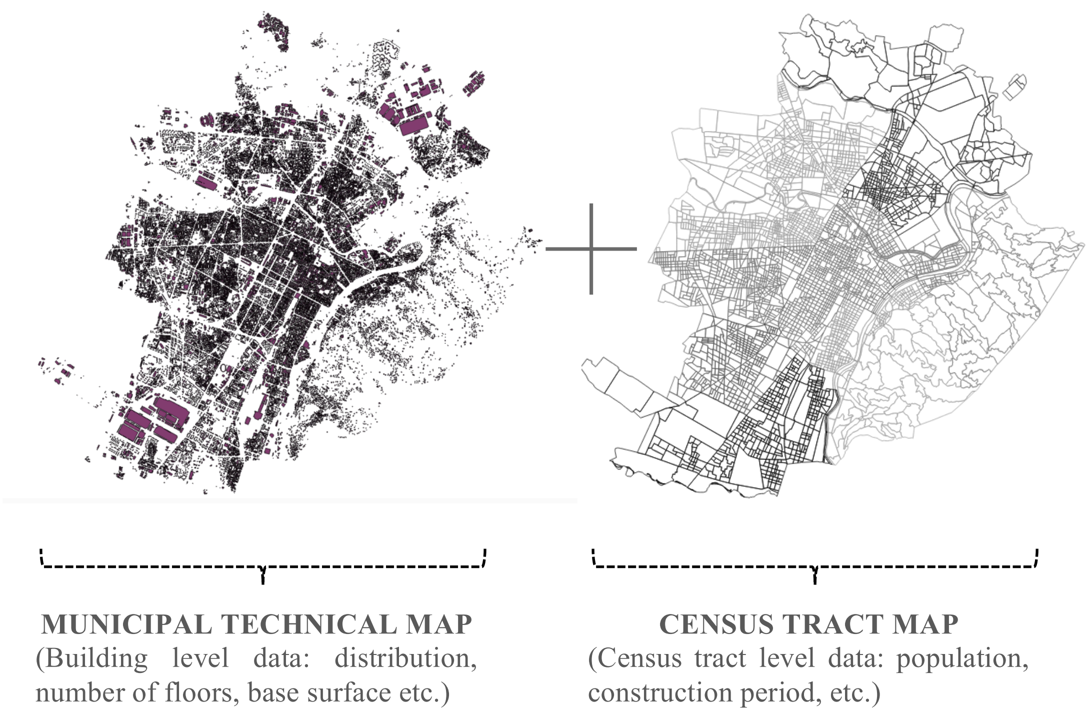


Figure 4-4: Matching the building layer with the statistical layer.

The layers match allows assigning a RB label to each residential building and a building class to each non-residential building of the city. Reference Buildings are regularly defined by referring to the main energy-intensive end-use service that, for the North of Italy, is space heating. Space heating is affected by five main variables (Mutani and Pariona, 2014): the climate, the construction period, the surface to volume ratio or shape factor (S/V), the percentage of heated volume and the peculiar characteristics of the stock that are related to the construction tradition. At the building stock level, according to previous literature (EU TABULA Project, 2012), residential RBs can be defined and clustered by knowing the construction period and the surface to volume ratio. Particularly, construction materials can be estimated by considering the traditions and the building regulation of the different construction periods. For non-residential buildings, the destination use was used as the main classification criterion in order to classify buildings.

In this thesis, the considered 9 construction periods refer to the statistical census for Torino (Città di Torino, 2017): C1 from 1900–1918; C2 from 1919–1945; C3 from 1946–1960; C4 from 1961– 1970; C5 from 1971–1980; C6 from 1981–1990; C7 from 1981–2000; C8 from 2001–2005; C9 from 2006-ongoing. An example of construction classes' distribution for district 1 is provided in Figure 4-5. It is important to highlight that until 1980 the energy regulation for buildings wasn't present (first energy regulation is the low 373/1976) and, as can be observed from Table 4-4, more than 93% of gross urban volume was built in this period. This consideration is uniformly distributed among all urban districts and it helps to understand that a low level of insulation characterizes most of the residential buildings.

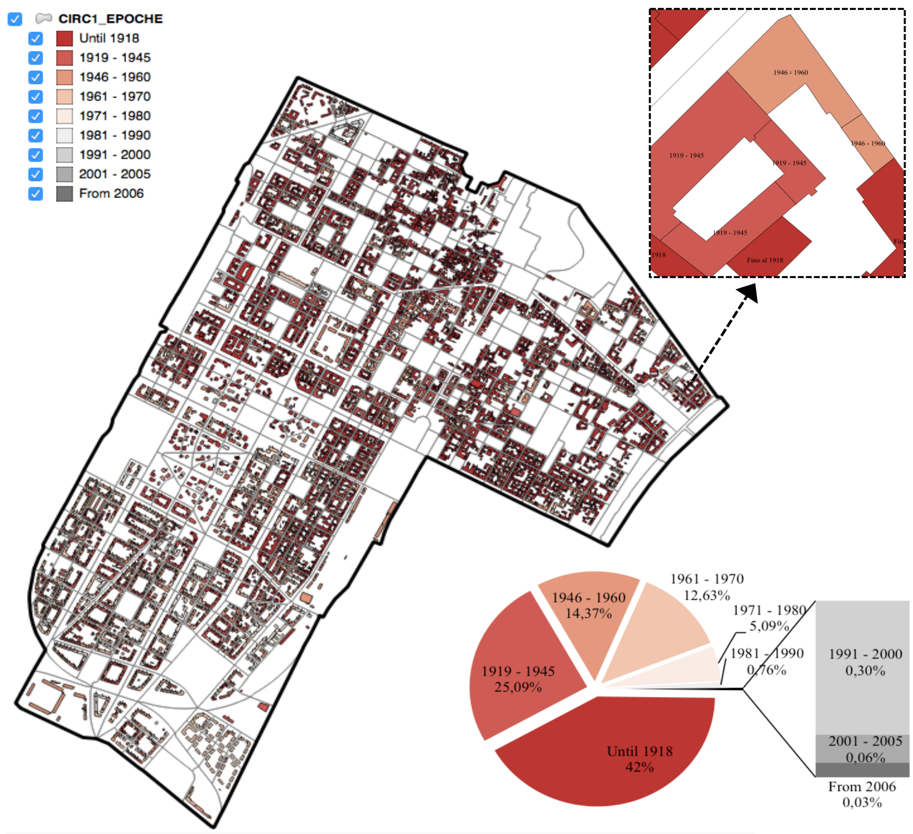


Figure 4-5: Construction periods of buildings in district 1 (graph referred to gross volume distribution).

From surface to volume ratios the compactness of the buildings can be understood, and consequently, the building types can be distinguished. The adopted classification refers to the (EU TABULA Project, 2012) and to (Ballarini et al., 2014) taking into account 4 building types: single families (SF) with S/V > 0.8 m^{-1}; terraced housed (TH) with 0.6 < S/V < 0.8 m^{-1}; multifamily (MF) with 0.4 < S/V < 0.6 m^{-1}; apartment blocks (AB) with S/V < 0.4 m^{-1}. As summarized in Table 4-4, more than 75% of the gross residential volume belongs to apartment block buildings (AB) and roughly 18% belongs to multi-families buildings (MF), meaning that compact buildings are prevailing in the urban environment. Nevertheless, while the distribution of construction periods is uniform among the urban districts, the distribution of building typologies it is not. As it can be observed in Figure 4-6a and in Figure 4-6b, even if apartment block buildings are always prevailing, the distribution among buildings types changes among urban districts. In particular, it changes from the city centre to the neighbourhoods, increasing the share of terraced and single-family houses (district 5,6,7,8 and 10) and decreasing the built environment volume per unit of land use.

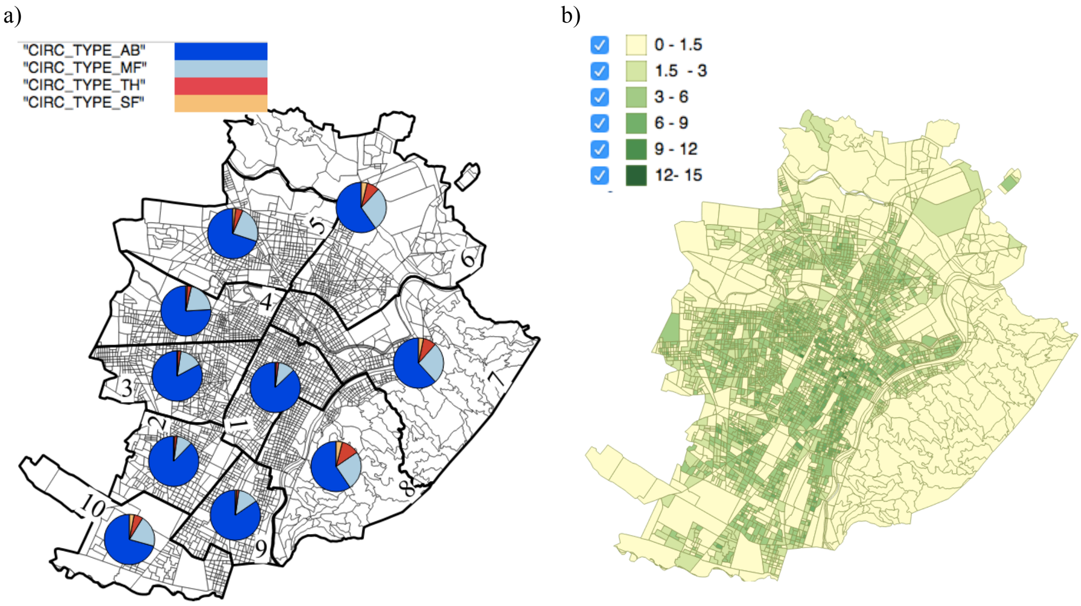


Figure 4-6: a) Distribution of building typology volumes among urban districts and b) ration between building volume and census tract surface (m^3/m^2).

From the combination of the 4 shape factors (S/V) and the 9 construction periods, 36 RBs can be identified (Table 4-5). From previous considerations, it is clear that apartment blocks and multifamily buildings represent the great majority (94% in terms of volume and 28,463 buildings) of the built environment. The ones built before the first energy regulation are 84% of the total volume (27,123 buildings) and in particular, apartment blocks built between 1961 and 1970 are the most representative, occupying 22% of the urban gross volume corresponding to 4291 buildings. This circumstance gives a special importance to building retrofit in the city, justifying also the specific choice of the planning objective.

For non-residential buildings, 6 destination uses were taken into account: schools, sports facilities, offices, little commercial activities, industrial activities and churches. Differently from residential buildings, the volume of non-residential buildings was calculated by using both the municipal technical map and the volumes provided in TAPE, following the methodology presented in (Mutani et al., 2016). As in Table 4-5, non-residential buildings occupy a total volume of about 36.23 Mm^3 of which 68.1% used for industrial activities, 16.4% for education, 11.8% are office buildings, 1.7% for sports activities, 1.4% are churches and 0.6% for little commercial activities.

Table 4-4. Urban distribution of residential RBs. n= number of buildings; V = gross volume (10^3 m^3).

		Construction periods									
		Before the first building energy regulation					Presence of a building energy regulation				Tot
		C1	C2	C3	C4	C5	C6	C7	C8	C9	
		Until 1918	1919-1945	1945-1960	1961-1970	1971-1980	1981-1990	1991-2000	2001-2005	From 2006	
AB	n	1970	3439	4399	4291	1860	432	177	56	31	16,655
	V	14,114	19,200	26,451	36,386	22,210	4967	1827	525	176	125,856
	%	11.2%	15.3%	21.0%	28.9%	17.6%	3.9%	1.5%	0.4%	0.1%	75.8%
MF	n	1628	2689	3515	2322	1010	323	201	87	33	11,808
	V	3964	6261	8762	6492	2936	962	637	285	101	30,401
	%	13.0%	20.6%	28.8%	21.4%	9.7%	3.2%	2.1%	0.9%	0.3%	18.3%
TH	n	1309	1609	2212	1240	595	216	119	29	19	7348
	V	1258	1492	2093	1203	601	243	135	36	18	7078
	%	17.8%	21.1%	29.6%	17.0%	8.5%	3.4%	1.9%	0.5%	0.3%	4.3%
SF	n	942	1265	1815	1012	462	193	101	23	11	5824
	V	430	543	807	459	225	91	46	11	6	2617
	%	16.4%	20.7%	30.8%	17.5%	8.6%	3.5%	1.7%	0.4%	0.2%	1.6%
Tot n		5849	9002	11941	8865	3927	1164	598	195	94	41,635
n (%)		14.0%	21.6%	28.7%	21.3%	9.4%	2.8%	1.4%	0.5%	0.2%	
Tot V		19,766	27,495	38,113	44,540	25,973	6264	2644	857	301	165,953
V(%)		11.9%	16.6%	23.0%	26.8%	15.7%	3.8%	1.6%	0.5%	0.2%	

Table 4-5. Urban distribution of non-residential building classes, V = gross volume (10^3 m^3).

	Schools	Sports facilities	Offices	Little Commercial	Industrial activities	Churches	Tot
V	5926	617	4268	223	24,677	518	36,228
V(%)	16.4%	1.7%	11.8%	0.6%	68.1%	1.4%	

All the presented work of building stock characterization is devoted to the further association of thermo-physical characteristics and/or space heating energy requirements to each residential RB and non-residential building types.

In the discussion section (Chapter 7) will be further analysed how data unavailability or low-quality data impacted on methodology limitations.

4.5 Discussion

The preparation and orientation phase is a very delicate and fundamental phase, setting the bases for the whole planning procedure. The three major actions of this phase (involving stakeholders, setting the objectives and collecting data) were performed for the case study of the thesis. These actions helped to create the planning framework, but at the same time highlighted major existing criticalities of this phase.

Actually, involving stakeholders was extremely problematic and time-consuming. Though it wasn’t a real planning exercise, entering in contact with the right reference persons required several iterations with long waiting time and not all stakeholders became available. Connections were established by means of interview or direct meeting in which it was possible to understand the interest of the district heating utility company and the Municipality in the proposed planning objective and to asking some of the necessary data. These difficulties underline the general problems of a participative planning approach: efforts required in involving stakeholders, different objectives and criteria of stakeholders, difficulties in sharing data. This last point introduces the other great criticality faced in this thesis: data collection. In fact, asking and collecting good quality data is a great challenge. In addition to the difficulties in engaging stakeholders, there is the lack of availability of open source data and the ununiformed structure of available data itself (different collection and sharing protocols in different institutions or in different offices of the same institution). In particular, difficulties were encountered in getting reliable top-down data related to the urban energy mix and the technology shares. In fact, the energy balance of the city is aged (it refers to 2005) and do not account renewable energy sources or their potential while the data related to technology shares are not available to the public. In the future, potentially, the data collection process will be enhanced through digitalization, reducing the data gap and allowing a more frequent update of datasets. As previously highlighted, fundamental in this phase was the use of GIS tools and the data provided by the district heating utility company (even if granted with extended deadlines). Thanks to GIS tools it was possible to characterize all the urban buildings: this, coupled with the real energy consumption data provided by the district heating utility company allowed to geo-referencing all the available energy data in order to develop energy consumptions models to fully characterize in terms of space heating energy demand the building stock for the whole city (Section 5.3.1).

Both the complications faced in involving stakeholders and in collecting data highlighted how current planning practices in Torino, but more generally in Italian Municipalities, are not confidential to an integrated energy planning approach.

A preliminary effort to sensitize stakeholders to this problem consisted in the organization of two workshops focused on integrated energy planning and its limitations in Italy. At these workshops were invited stakeholders from Italian Regions, Municipality and utility companies. The first workshop was held in Torino the 19th April 2016 (Politecnico di Torino LAME, 2016) with the goal of sharing best practices in integrated energy planning while the second workshop was co-organized with ENEA (ENEA and Politecnico di Torino LAME, 2017) and held in Rome the 22nd May 2017 with the objective of creating a network of energy planning stakeholders. From the workshops the need for guidelines and shared frameworks to support energy planning at the local scale emerged, in particular concerning what should actively be done by public offices: data collection and management. Particularly interesting, during the last workshop, a questionnaire was delivered to the participant in order to understand which is the interest of stakeholders in such events, in the creation of a network and on local energy planning themes and activities. The results are presented for 18 participants: 3 Regional stakeholders, 2 energy utility stakeholders and 13 academic and private stakeholders. In Figure 4-7, it is possible to observe that all the participants showed their interest in the creation of a network focused on energy planning at the local scale while expecting an active participation (intended as a contribution in the organization of events) from stakeholders is more challenging, especially outside of academia. Figure 4-8 presents a deeper analysis of the willing to contribute to the organization and management of some of the possible local energy planning network activities. As major consideration, it is possible to state that a consistent contribution in the management of the network (e.g. organization of events, the creation of website) may not be expected, while a more active involvement may be expected in educational and project-related activities. This stresses the fact that in order to really activate and promote a network or a common planning framework, a very strong commitment and robust motivation will be necessary. **Figure 4-9** highlights the themes and activities that interested mostly the participants and were considered crucial in a successful planning framework. Almost all agreed on the importance in disposing of open source data platforms and the majority of participants recognized the importance of GIS tools, Spatial Decision Support Systems (SDSS) and Building Information Modelling (BIM). Another commonly agreed point was related to sharing best practices: from successfully concluded planning procedures by other realities, it is possible to learn important lessons and practices. Discordant opinions instead resulted in the other themes: a national model to support regional energy planning was considered significant with a great majority only by the participants from regions and academia (utility strategies may have different objectives from the regional ones); the involvement of ESCOs and utilities were recognized important only by utilities themselves, index that a participative integrated approach is far from traditional practices; finding economic resources was reported very important by regions and in part by utilities, while academia resulted mostly indifferent or not interested.

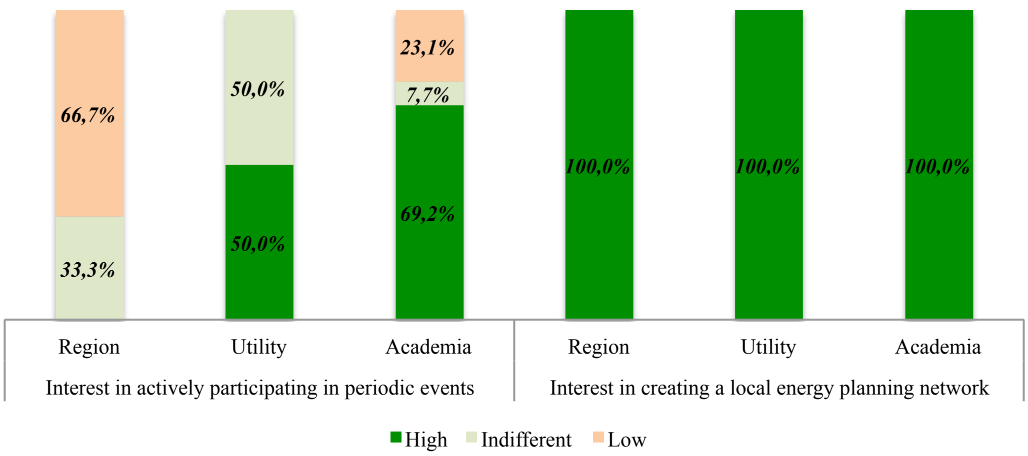


Figure 4-7: Questionnaire results related to the interest in creating and participating to a local energy planning network.

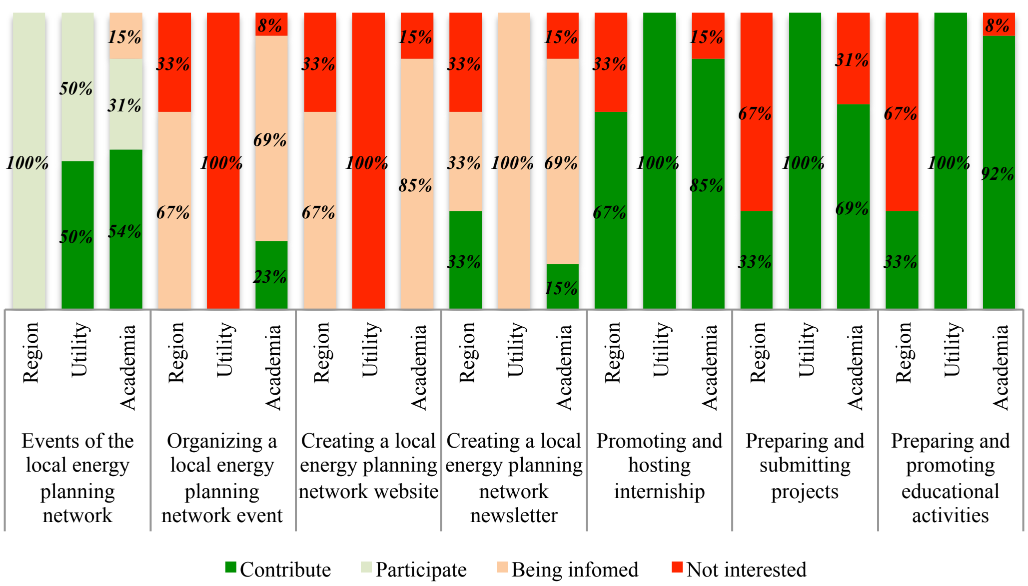


Figure 4-8: Questionnaire results related to the interest in the possible events and activities promoted by an energy planning network.

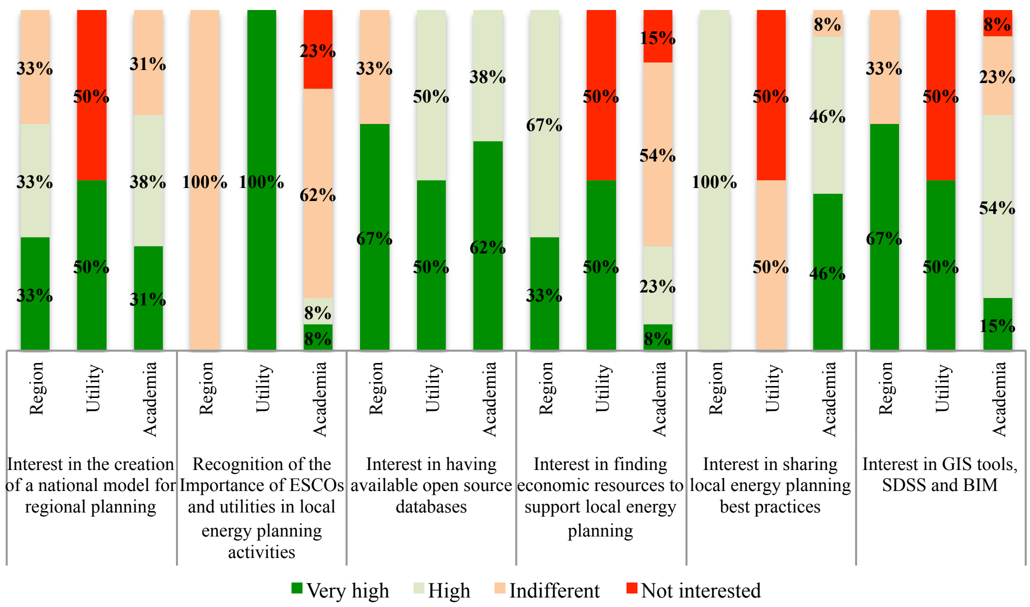


Figure 4-9: Questionnaire results related to the interest in the possible themes proposed by a local energy planning network.

4.6 Conclusions

In this chapter, the three principal actions of the Preparation and Orientation phase are described and performed for the city of Torino. There are no systematic ways to perform this phase, but it should be clear that the goals of the phase are: (i) conceptual: to understand the system and setting the objectives and problems and (ii) operative: engaging all the stakeholders, selecting planning methods and tools and collecting the data.

Reflecting the city context, energy situation and literature gaps, the planning objective was defined as the understanding of the long-term system dependency of energy savings derived from several building retrofit scenarios under different heat supply decarbonization strategies. This objective was considered very important being Torino a district heated city: the energy demand reduction will indeed impact on the investment strategies and the operation of the network. From the nature of the planning objective, comprehensive energy systems models and tools were identified as suitable planning methodologies to be further adopted in the next planning phase. Indeed, these planning methodologies allow multi commodities (e.g., electricity, gas, etc.) and multi-sectoral (household, tertiary etc.) energy planning taking systematically into account the different dimensions of environment, technical feasibility and economy.

The process of stakeholders' involvement and data collection was very time-consuming and challenging, highlighting the lack of a participative integrated energy planning in common energy planning procedures. On the one hand, involving stakeholders requires many efforts in creating stable reference contacts and on the other hand, data availability is scarce, rarely open source and often collected with ununiformed protocols. These reflections highlight the importance to push future research and practice to take into account a participative and integrated planning process by reinforcing the collaboration between different research disciplines dealing with socio-economic, institutional and technical aspects with attention to spatial issues. In fact, spatial GIS tools were fundamental in performing the data collection process and are strongly suggested for all territorial analyses related to urban energy planning.

To conclude, this planning phase is fundamental to the success of the whole planning procedure. There is not a well-defined systematic way to perform it, but the objectives are clear and their fulfilment strongly depends by the availability of good quality data, the planner abilities and inclination of different planning stockholder to be actively involved in the procedure.

Chapter 5

Detailed energy modelling phase: simulation approach

5.1 Overview

This chapter presents an urban energy system simulation model with novel features in order to study the specific interactions between energy efficient buildings and the development of urban heat strategies (Figure 5-1).

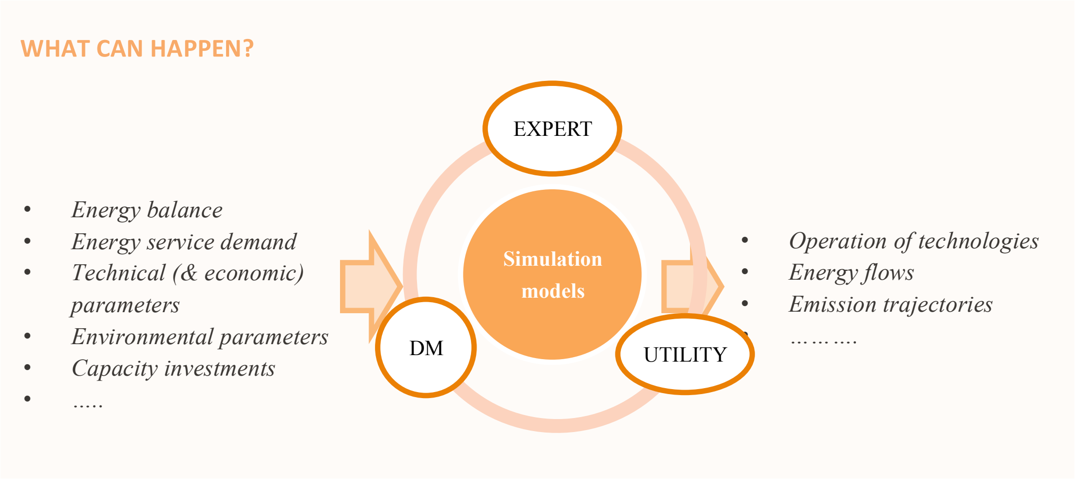


Figure 5-1: Schematic of energy system simulation models.

Key findings:

Methodology:

- The availability of monitored energy consumption data contributes to better estimate urban energy consumption, including morphological aspects and occupant behaviour.
- The cost-optimal methodology help to identify a suitable range of cost-effective retrofit measures across the building stock, supporting the selection of measures for the scenario analysis.
- The methodology enables explorative scenarios to understand their impacts on the energy system with respect to important economic and planning considerations.
- The methodology provides a useful approach to assessing prospective pathways forward for integrated building and district energy solutions.
- Scaling up perspectives from a single building level to an energy system level would help to capture interdependencies between supply and demand sectors that are traditionally treated individually.

Case study:

- Urban reference consumption can be set as 9.19 TWh of which 62% residential consumption and 38% non-residential. Many buildings host commercial activities in the ground floor that may impact the total urban consumption.
- The cost-optimal range of energy intensity reduction is between 13 and 21 kWh/m^3 while the costs are comprised between about 45 and 67 €/m^3.
- Building energy retrofit measures should be planned with the purpose of reducing energy intensive thermal peaks and not to decrease use of the existing base load plants. Variation of the heat profile would also change the size of new investments for baseload plants, and so new capacity should be planned carefully with respect to anticipated building measures.
- Results stress the fundamental role of finding synergies between energy saving measures and new heat supply investments.

Key limitations:

- The methodology already requires input to know the configuration of the local energy system as well as the technologies that would be taken into account.
- Pathways creation by linking energy system "pictures" that are dynamic over a one year time-period, but not over the whole time horizon.

Declarations.

Part of the work described in this Chapter was also previously published in the following publications, further reported in Appendix A of this thesis.

- Delmastro C., Mutani G., Corgnati S.P. (2016). Energy Policy, 99, pp.42-56.
- Mutani G., Delmastro C., Gargiulo G., Corgnati S.P. (2016). Energy Procedia, 101, pp.384-391.
- Delmastro C., Martinsson F., Dulac J., Corgnati S.P. (2017). Energy, 138, pp.1209-1220.
- Delmastro C., Martinsson F., Mutani G., Corgnati S.P. (2017). Proc. Engineering, 198, pp. 386-397.
- International Energy Agency, ETP 2016, Chapter 4, pp. 202-205.

5.2 Introduction

This chapter focuses on the use of scenario tools/models that "*simulate the operation of a given energy system to supply a given set of energy demands"* and *"are operated in hourly time-steps over a one-year time-period*" (Connolly et al., 2010). Simulation tools are mostly focused on the operation of the energy system; therefore they are very helpful in supporting medium/short-term energy planning by proposing "forecasts", "what if" and "explorative" scenarios (Börjeson et al., 2006) of how the system may evolve.

Limited studies have tried to investigate, from a system perspective, the possible synergies and methodologies to support a holistic approach to building renovation and DH investments or expansions through a simulation approach. The study of (Lidberg et al., 2016) analysed to what point buildings could be refurbished, taking into account DH utilisation and electricity production. Similar analysis by (Lundström and Wallin, 2016) assessed that with a "greener" heat production mix, the benefits of building thermal demand reduction decrease; (Difs et al., 2010) verifies that for both an economic and an environmental perspective, the reduction of electricity consumption needs to be prioritised with respect to savings in DH. Research by (Truong et al., 2014) and (Thellufsen and Lund, 2015) confirmed the importance of electricity savings. (Rolfsman, 2002) studied how several renovation measures in buildings affect the CO_2 emissions under different system perspectives. (Åberg and Henning, 2011) analysed the combined effects of building renovation in DH systems, finding that if co-produced electricity replaces electricity from coal-fired condensing power plants, a 20% heat demand reduction is optimal for the Swedish energy system. In Denmark, (Lund et al., 2014) identified a 50% decrease in net heat demands of new buildings or buildings that need to be renovated as a suitable strategy when 2/3 of heat is provided by DH and 1/3 by individual heat pumps. Results from (Sperling and Möller, 2012) showed that combing building renovation with the expansion of a DH network improves the overall fuel efficiency of the system.

From previous studies, it is clear that the system dependency of energy savings still needs to be better understood. This research presents a methodology for supporting local authorities, researchers and utilities in investigating the impacts (in terms of energy, emissions, and costs) of several market strategies involving different building renovation measures and new technology investment choices over long-term horizons in cities with DH. The novelty of the approach consists of the integration of both buildings and DH sectorial models through an integration module to develop long-term explorative scenarios. Compared to previous methods, this approach allows a comparison of the energetic, environmental and economic impacts of several demand/supply measures over long-term horizons, using a "matrix" of potential combinations of building renovation measures with DH investments. In particular, the approach was developed considering the typically available data in Europe, and it pulls upon GIS software (typically used in planning activities), building simulation and district heating network simulation models. This approach allows for a more comprehensive energy system analysis, typically applied to a larger scale with specific software (e.g., EnergyPLAN (Lund and Münster, 2003)), by guarantying the sufficient level of detail, particularly in terms of demand disaggregation, necessary for local applications. The methodology does not seek to replace other simulation or complex energy system modelling platforms but rather to generate suitable indices through the combined methods upon which sound and informed decisions can be made regarding the appropriate direction for investments with respect to aforementioned objectives. The analysed area includes 100 Mm^3 of buildings, of which 57 Mm^3 district heated and the remaining assumed all heated by gas boilers. The modelling framework allows expanding the district heating network to supply the whole building volumes or to introduce new distributed generation plants. To keep the scenarios simple and easily understandable, in this thesis, they will involve only measures about district heating network expansion and building retrofit, leaving open the introduction of alternative distributed generation options for future applications.

In this Chapter, the proposed comprehensive methodology is applied to the case study city of Torino. Section 5.3 is dedicated to the description of the methodology and in particular, Section 5.3.1 is dedicated to building energy modelling, Section 5.3.2 is dedicated to district heating modelling while Section 5.3.3 describes the integrated analysis. The results are presented in Section 5.4 and discussed in Section 0. Section 5.6 summarises the main conclusions and insights derived from the proposed research.

5.3 Methodology

The methodology is developed to provide market insights concerning building retrofit and DH network investment plans under an economic, energetic and environmental perspective. The focus is on the long-term possible energy system evolutions considering several heat strategy options. A buildings stock model for thermal demand estimation and a DH simulation model are integrated for evaluating the energy saving potential and the associated energy system total cost (TSC) and emissions reduction, under different investment scenario assumptions (Figure 5-2). The proposed model is characterized by a time horizon from 2015 to 2050, divided into 4 time periods, and by a hourly time resolution.

The building model generates space-heating profiles relative to the existing building stock and its progressive retrofit and calculates the life cycle cost discounted at 2015 level. Space heating demand variations during the time horizon are input to a DH simulation model that calculate the heat production costs when the system is subjected to several investment assumptions. All these information are merged through an integration module that calculates the TSC and global carbon emissions considering the costs and emissions reductions from both the buildings model and the DH model.

This Section is further divided into three main sub-paragraphs: Section 5.3.1 describes the building model, Section 5.3.2 is dedicated to the district heating model and the third section is devoted to their integration (Section 5.3.3).

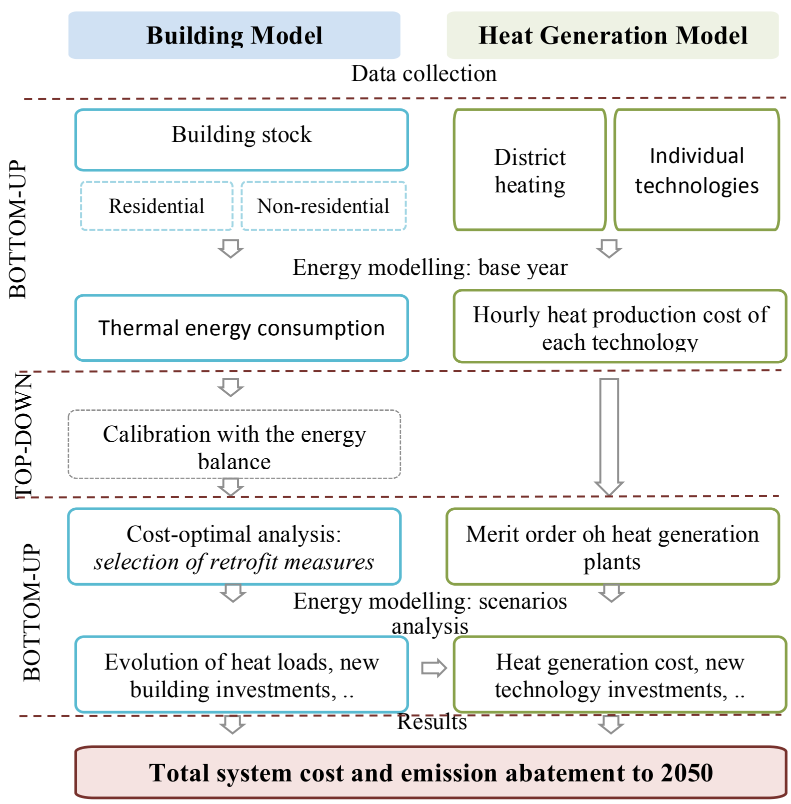


Figure 5-2: Schematic of the methodology. Adapted from (Delmastro et al., 2017a).

5.3.1 Building energy modelling

The procedure described in this section enables to evaluate the building stock energy performances and to identify the retrofit measures and their cost to be further adopted in the planning modelling activities. The section is divided into four steps: the analysis of a building sample (Section 5.3.1.1), the characterization of urban space heating energy consumption (Section 5.3.1.2), the identification of retrofit measures (Section 5.3.1.3) and the generation of urban building energy scenarios (Section 5.3.1.4). The building analysis was performed on the whole urban area, but the scenarios analysis is focused on an area of 100 Mm^3, including the current district heated area in 2015 (57 Mm^3) plus a potential area of network expansion (43 Mm^3).

5.3.1.1. Building sample data

Two different extreme situations can be observed in different urban contests: an elevate availability of real energy consumption data or not enough energy consumption data to perform statistical evaluations. In the second case, when real energy performance data are not available, Reference Buildings allow assessing energy consumption by using energy simulation software (e.g., EnergyPlus) or previous literature information. Nevertheless, it is well known that there is a gap between the energy consumption evaluated at by simulation software and real energy performances mainly for morphological aspects (Delmastro et al., 2015) and occupant behaviour (D'Oca et al., 2018).

For Torino, all the Reference Buildings were previously characterized by means of energy simulation in the framework of the (EU TABULA Project, 2012). Nevertheless, to reduce the previously cited real/simulated energy "gap" problems, real space heating (SH) energy consumption data (with monthly detail for three consecutive heating seasons: 2011/2012, 2012/2013 and 2013/2014) of a sample of 300 buildings, sited in a representative district, were analysed (11 non-residential buildings and 289 residential buildings). All the data were provided by the local district heating company and were characterized by information relative to volume and space heating energy consumptions. All the buildings were geo-referenced in the map for associating a construction period to each building and for evaluating the building volumes. Non-residential buildings were excluded from the sample analysis because the destination use was unknown. Furthermore, due to some discordance between the calculated heated volume with GIS and heated volume provided by the district heating company, some buildings were a priori discharged from the analysis and the sample was reduced to 233 buildings. Since all the sample buildings are connected to the district-heating network, they are all apartments blocks (AB) or multifamily buildings (MF). The 233 residential buildings occupy a total volume of 1.89 Mm^3 of which 1.77 Mm^3 Apartment Blocks (AB) and 0.12 Mm^3 Multi-Family buildings (MF) with an average gross heated volume of 8096 m^3 per building (min 3000 and max 34,000 m^3) and average shape factor (S/V) of 0.32 m^{-1} (min 0.21 m^{-1} max 0.48 m^{-1}) (Table 5-1). As it can be seen in Figure 5-3, the building sample covers construction periods from 1918 to 2000 but with most of the building volume built between 1961 and 1970 (36.3%). The total space heating consumption was 75.1

GWh, with average yearly space heating consumption per building of 327 MWh/y/building and average space heating intensity per building of 40.32 kWh/m^3. The relationship between space heating consumption and volume is quite linear as it can be seen in Figure 5-4. To proceed with the energy analysis, all the 233 buildings analysed were labelled with a RB class (defined according to S/V and construction period) as described in Chapter 4. All the energy-use data for space heating were then normalized considering the regulatory standard Heating Degree Day (HDD) of the city of Torino (2617 HDD). The normalized space heating energy intensities (kWh/m^3) were evaluated for each building (considering the three seasons and the reference HDD). A normal distribution was applied to the energy intensities data in order to exclude buildings with atypical energy-uses (e.g., already retrofitted buildings, empty buildings, errors in volume associations etc.). The distribution of average energy intensities per building types is visible in Figure 5-5. As expected, the lower the building compactness and the higher the space heating energy intensities.

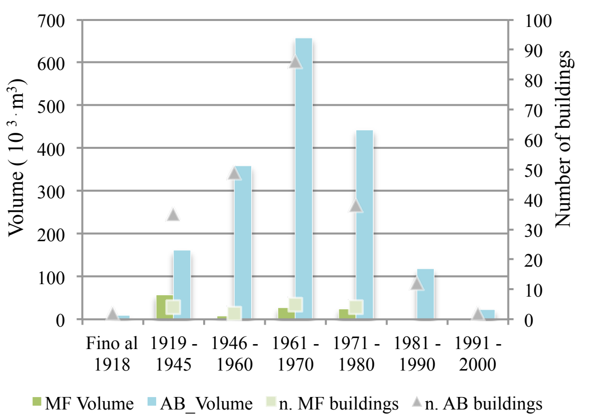


Figure 5-3: Volume distribution of sample residential buildings per building type and construction period.

Table 5-1. Characteristics of sample residential buildings.

	MF	AB	Average/ building
Number of buildings	15	218	/
Volume (Mm^3)	0.12	1.77	8096 m^3
S/V average (m^{-1})	0.42	0.31	0.32

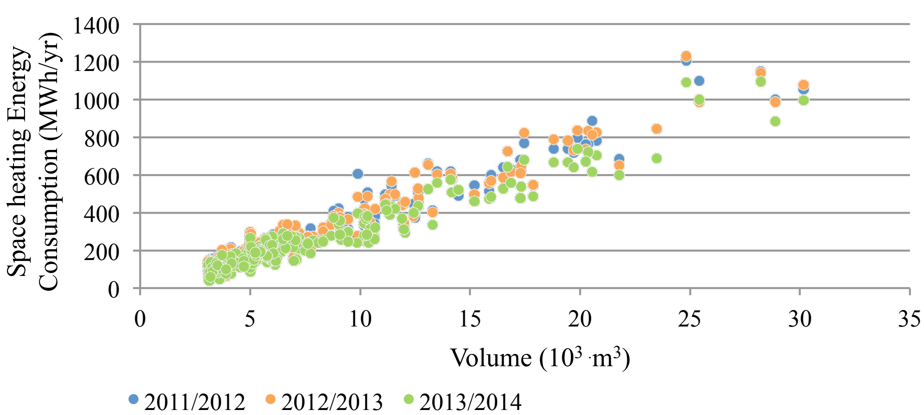


Figure 5-4: Space heating energy consumption of sample residential buildings.

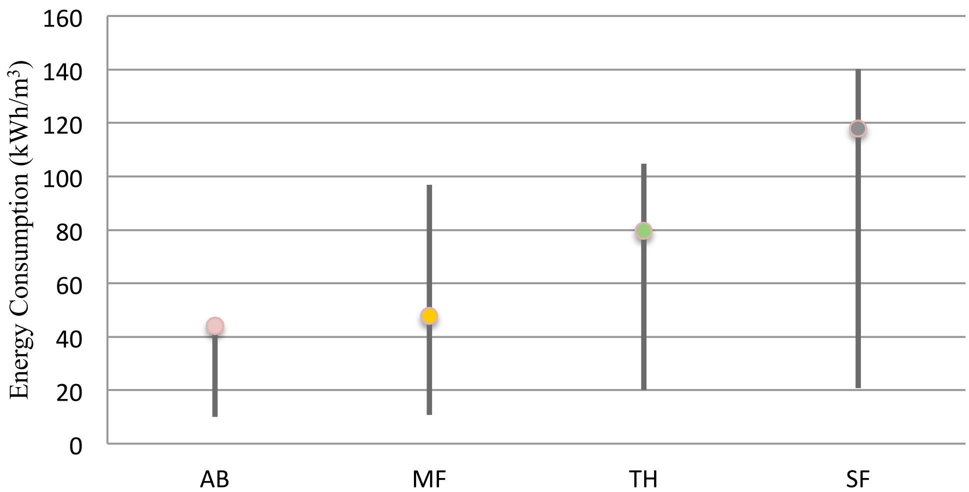


Figure 5-5: Space heating energy intensities distribution for the sample residential buildings (Delmastro et al., 2016a).

The described information related to sample data supported the estimation of urban thermal consumption for this thesis as further described in the next session (Section 5.3.1.2).

5.3.1.2. Characterization of urban space heating consumption

The goal of this section is to describe a methodology for associating to each Reference Building a space heating energy requirement that is able to statistically represent the thermo-physical behaviour of the relative archetype. This phase is necessary in order to assess the energy performance of the urban built environment. This step is based on the use of both bottom-up (building level data) and top-down (energy balance) data. In fact, once the built environment is characterized in terms of RB and thus of energy consumption, comparing the bottom-up and top-down energy-use data for the residential sector allows having calibration with the urban energy balance. Thus, a calibration coefficient should be determined in order to have more realistic results.

As initial data elaboration, a normal distribution was applied to the previously elaborated energy intensities of sample residential buildings in order to find the reference energy performance for each archetype belonging to the sample set (Mutani and Pariona, 2014). Figure 5-6 shows the normal distribution relative to Apartment Block built between 1961 and 1970 before and after the exclusion of atypical buildings.

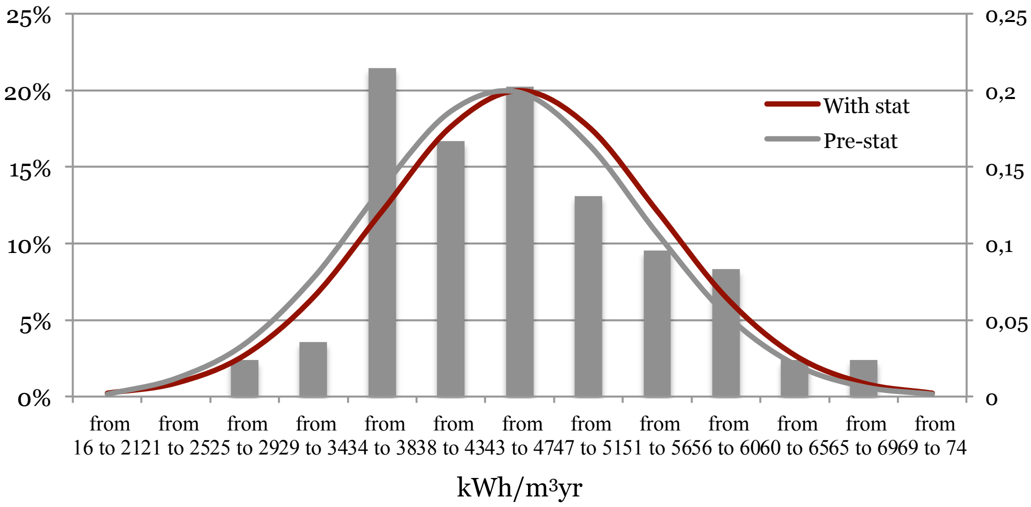


Figure 5-6: Normal distribution of normalized space heating energy intensities for AB built from 1961 and 1970 (AB-C4) (Delmastro et al., 2016a).

The resulting space heating energy intensities were compared to the other works relative to the city of Torino: the TABULA project (EU TABULA Project, 2012) based on simulation and the work of (Mutani and Pariona, 2014) (Figure 5-7).

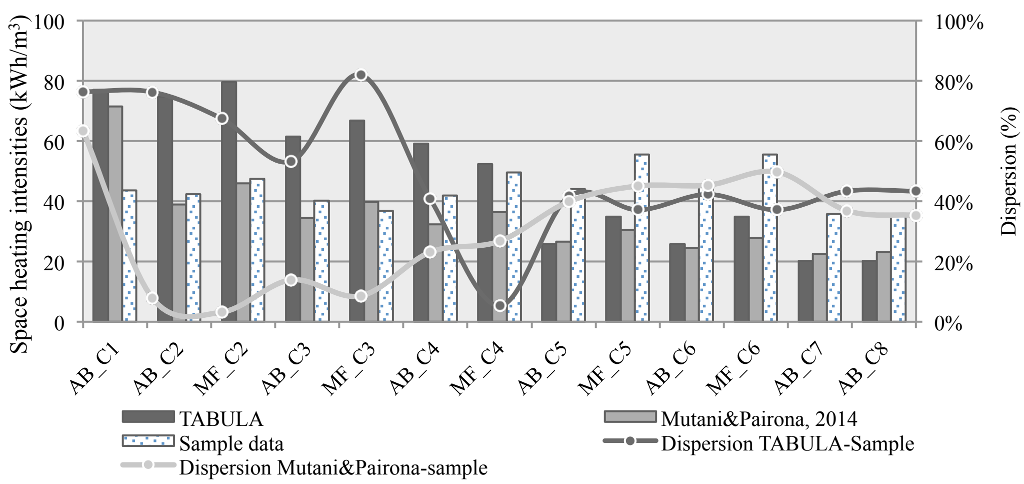


Figure 5-7: Comparison of space heating energy intensities for between sample buildings, TABULA project and the work of (Mutani and Pairona, 2014). C1-9 refers to the construction periods as in Section 4. The work of (Mutani and Pairona, 2014) is already calibrated with the energy balance.

As it can be observed in Figure 5-7, compared to the other works, using the data from the TABULA project lead to an overestimation of building space heating consumptions for the buildings built from C1 to C4, while are instead very similar to work of (Mutani and Pairona, 2014). Many reasons may affect this trend such as different assumptions on building orientation, microclimate, shadings, occupants, etc.

From C5 ongoing, the energy consumptions of sample buildings are much higher compared to the other two works, probably meaning that even if the energy regulation was activated, some buildings were built without correctly applying insulation materials or were characterized by different operation schedules. In particular, many buildings host commercial activities on the ground floor that may impact the total urban consumption. However, the space heating energy consumptions of the buildings for which real consumption data were not available were assumed as the ones of the (EU TABULA Project, 2012). In addition, considering the very low variability of energy performances in some RBs, buildings in C5 (built from1971-1980) were grouped together with the ones in C6 (1981-1990) for MF, TH and SF, while buildings in C7 (1991-2000) were grouped with building in C8 (2000-2005) for all building types. Thus, the total number of RBs was reduced to 29. The considered values of space heating energy intensities in further steps are visible in Figure 5-8.

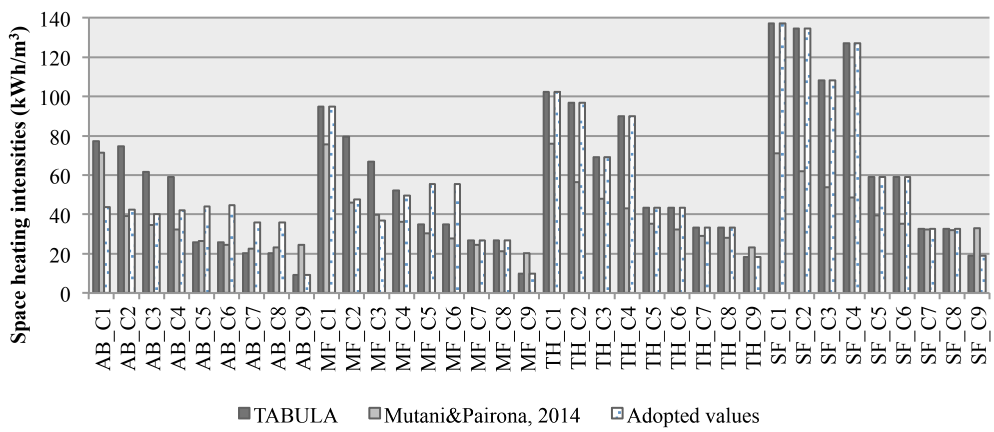


Figure 5-8: Space heating energy intensities for the different RBs. C1-9 refers to the construction periods as in Chapter 4. The work of (Mutani and Pairona, 2014) is already calibrated with the energy balance.

At this stage, the evaluation of urban space heating energy consumption for all pre-2006 buildings can be completed by calibrating the archetype bottom-up results, scaled up by a volume weighting function, with the space heating value provided by the energy balance. The calibration is needed because the estimated energy-use developed in the bottom-up approach does not take into account important factors such as the spatial variability in: solar gains, indoor/outdoor air temperatures and, mainly, the retrofit of buildings that may have changed their energy consumptions over the years. Thus, to consider these variables and to adapt the results to real energy consumption data, the EP associated to each RB should be multiplied by a factor that is typical of the analysed built environment (Mutani and Vicentini, 2013b). As previously observed, the city energy balance refers to 2005 (Città di Torino, 2012) and for residential buildings is 6.84 TWh at the 2005 HDD (2703 HDD), including cooking and hot water end-uses. From current literature and statistics (Fracastoro and Serraino, 2011) hot water and cooking services account for about 14% of residential thermal energy consumptions and space heating for 86%. Considering the energy balance, it can thus be assessed that 5.88 TWh represents the space heating energy consumption of pre-2006 buildings of the city of Turin at 2703 HDD (or 5.69 TWh at 2617 HDD). The obtained calibration factor derived from the elaborations of the building sample data is 0.92 (overestimation). This result is again compared with the other two works. To match the energy balance value, the space heating energy intensities of (Mutani and Pairona, 2014) needed a calibration factor of 1.24 (underestimation), the ones of TABULA of 0.64 (overestimation). Taking into account these calibration factors, it was decided to use the space heating intensities derived from sample data elaborations. To this space heating value of 5.69 TWh, the space-heating quota associated to buildings built between 2005 and 2015 should be added (0.3 Mm^3 consuming 4.1 GWh for space heating).

Concerning non-residential buildings, the total energy consumption derived from the city energy balance (Città di Torino, 2012). Non residential buildings were divided into six destination uses according to volume distributions derived by GIS analysis (Mutani et al., 2016). By combining the building volume distributions for each census section and by applying several statistical analyses, it is consequently possible to calculate the average urban energy intensity of non-residential buildings classified for their destination use (Table 5-2, (Mutani et al., 2016)).

Table 5-2. Linear models for specific space heating (kWh/m^3) as a function of the heated volume (2703 HDD). From (Mutani et al., 2016).

	Schools	Sports facilities	Offices	Commercial (little activities)	Industrial activities	Churches
Heated volume m^3	5,926,337	616,896	4,267,591	222,578	24,677,166	517,667
kWh/m^3	30.01	41.45	24.89	10.08	125.84	3.26

Concluding, considering the normative HDD (2617 HDD at 20°C) and the previously described energy intensities, the total urban space heating consumption can be set as 9.19 TWh of which 62% residential and 38% non-residential. The heat densities per census section can be observed in Figure 5-9a. As expected, the higher heat densities can be detected in the areas close to the city centre, while higher space heating intensities in the areas where the compactness of buildings is lower (Figure 5-9b).

a) b)

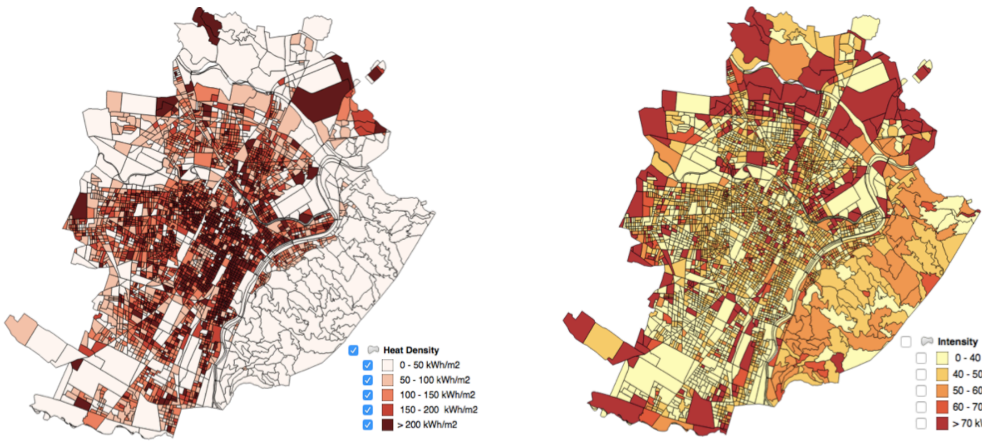


Figure 5-9: a) Heat density per unit of census sections' surface kWh/m^2 and b) Distribution of space heating intensity kWh/m^3 (Mutani et al., 2016).

5.3.1.3. Identification of residential building retrofit measures

The goal of this section is to identify suitable retrofit measures to be further used in the planning and scenarios analysis. Therefore, the principal output of this section is a mix of cost-optimal retrofit packages for the urban building stock. The cost-optimal methodology was selected since proposed in the EPBD recast (European Parliament, 2010) and was applied to all the previously identified RBs in the city of Torino. The main relevance of this step is that by applying the cost-optimal analysis at the stock level is it possible to have an indication on the suitable range of energy performance and related costs that are reasonable to promote for the building stock from an economic and energy perspective. In addition to the planning goal, this can help policymakers to understand at which level a fiscal policy can be targeted or which are the retrofit interventions that can be funded for the different RBs.

This step was performed by calculating the size of each RB component (polygonal geometry from GIS) and by associating to each component a thermal transmittances value. The thermal transmittances of building envelope components are helpful to evaluate the effects of renovation measures. Thermal transmittances values can be assigned by using different approaches (e.g., the energy signature, correlation with literature data etc.). In this thesis, the values of thermal transmittance were derived from the (EU TABULA Project, 2012): the values were associated to the building types by considering the most common material associated to each component in each construction period and for each building type. Figure 5-10 summarizes the thermal transmittances of building components for the most frequent and more recently built RBs in the stock.

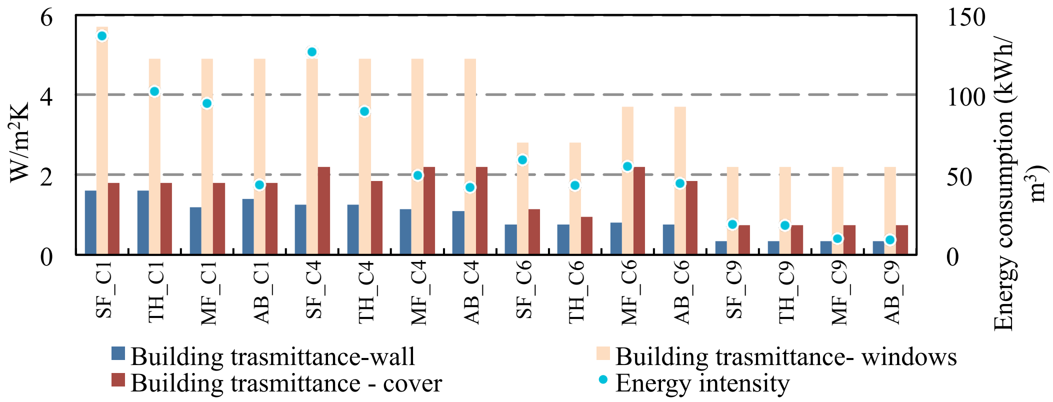


Figure 5-10: Thermal transmittances for windows, roofs and walls and space heating energy intensities for some building types. (Delmastro et al., 2016a).

The concept of cost optimal level is referred to the quantity of primary energy to supply the energy demand of a building that corresponds to the lowest lifecycle cost in the whole life cycle according to the European Standard EN 15459:2007 (Becchio et al., 2015; Hamdy et al., 2013). A cost-optimal analysis implies the cost estimation for different design alternatives involving several configurations of the building envelope, the energy system and their combinations. In this thesis, the cost-optimal methodology was performed focusing on space heating consumption only, being the core focus of whole case study. In the cost-optimal methodology, the global cost includes capital, fuel, operations and maintenance costs [O&M] and it is referred to a single building ($C_{g,b}$, in €/m^3). $C_{g,b}$ is evaluated over a calculation period t and it is calculated as in Eq. 1.

$$C_{g,b} = C_{Inv} + \sum_j \left[\sum_{i=1}^{t} \left(C_{y,j}(i) \times d\ (i)\right) - R_{f,j}(i)\right] \qquad (1)$$

Where C_{Inv} (€) is the investment cost at the year t=0; $C_{y,j}(i)$ (€/year) is the yearly cost (at time t=i) related to component j (O&M, running cost, substitution cost); d (i) (%) is the discount rate at the year i; and $R_{f,j}(i)$ (€) is residual value of the component j at time i.

A total of 196 retrofit packages were analysed: 4 measures for each reference archetype plus 14 measures for the most diffused RB for each building type. The Standard and Advanced packages, referred to the ones proposed by (EU TABULA Project, 2012), were updated taking into account current regulation (D.M. 26/6/15; 2010/31/UE). The retrofit packages involve progressive interventions ranging from simple regulation to deep retrofit and their impact on energy consumptions was estimated by building simulations derived from previous works and then re-scaled to the current building stock energy performances. Deep retrofit refers to envelope insulation measures or other building envelope improvements as well as improvements of the heat distribution system within the building. The cost of each measure was evaluated through the reference technical cost data of single component and intervention available at (Regione Piemonte, 2016) and by knowing the geometrical characteristics of all buildings (to estimate the average cost, average size of building surfaces and components was considered). Then, the cost-optimal methodology was applied to all the RBs, considering their volume distribution throughout the urban area. As literature suggests, the discount rate was assumed equal to 3.5% and the calculation period is equal to 30 years, as generally assumed for cost-optimal analyses. It was assumed that the efficiency of the DH heat exchangers in the buildings is 0.9. The remaining buildings are heated by non-condensing gas boilers with an efficiency of 0.8 that are progressively replaced with condensing boilers with efficiencies up to 0.95. No other distributed generation options was included in this analysis.

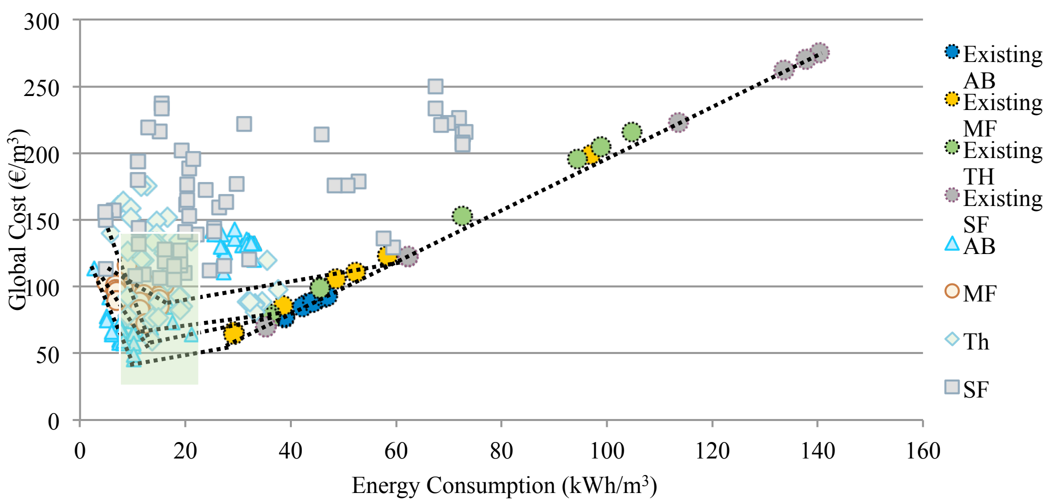


Figure 5-11: Cost-optimal analysis applied at the stock level, indication of suitable range of energy demand reduction. AB=apartment block, MF= multi-family, TH=terraced house, SF= single-family (Delmastro et al., 2016a).

In Figure 5-11, results of the cost-optimal analysis for the whole building stock are shown. The goal is to identify the level of energy intensity reduction that is suitable to promote for the building stock, that in this case is between 13 and 21 kWh/m^3 while the costs are comprised between about 45 and 67 €/m^3 (without considering fiscal policies). This step doesn't aim at identifying specific retrofit measures, but provides an indication of costs and energy performance to be further adopted in the scenarios analysis, taking in mind that specific design features should be then decided at the single building level. In buildings characterized by high compactness (AB and MF), the retrofit of the envelope is less effective compared to lower size buildings. For these buildings, the improvement of the energy efficiency of the energy system is needed. Condensing gas boilers are highlighted as the best solution at the single building level, but from a wider communitarian perspective, the connection to the DH network is more advantageous considering the highly efficient technological mix of the city. The cost-optimal solutions for Apartment Block buildings built between 1961 and 1970 (analysed with higher level of details) involve: 1) if energy savings are a priority: the substitution of windows, envelope retrofit, the connection to the DH network, zone regulation and thermal insulation of the distribution system; or: 2) if economic savings are a priority: connection to the district heating network, zone regulation and thermal insulation of the distribution system. The cost-optimal measures associated to buildings with low compactness (single family and terraced houses) include, instead, envelope retrofit, windows replacement and boiler substitution. Larger energy savings can be reached by adding roof insulation to the retrofit package. Table 5-3 shows an example of the values of thermal transmittance and thickness of envelope materials resulted from the cost-optimal analysis. The intervention is selected as a retrofit measure for apartment block buildings built between 1961 and 1970 in the city of Torino.

Table 5-3. Envelope renovation details of an Apartment Block built between 1961 and 1970. From (Delmastro et al., 2016a; Guala, 2013).

AB_C4	External Wall	Counterwall- vertical towards non heated spaces	Counterwall- floor slabs towards non heated spaces	Windows
Transmittance ($W/m^2/K$)	< 0.25	< 0.3	< 0.26	< 1.2
Thickness (cm)	8	8	8	

As it can be observed, most of the measures resulted from the cost-optimal analysis involve deep retrofit with envelope intervention, requiring particular attention when applied to multi-family buildings. In fact, in general, their feasibility depends on the actual fiscal policies, the socio-economic condition of people (the willingness to invest) and the urban environmental goals, but for multi-family buildings also depends on the opinions, which might be discordant, of all the building occupants. Generate retrofit scenarios may, therefore, encounter such difficulties, therefore, it can be assumed that once a building performs a regular maintenance intervention (e.g. façade renovation) it also associates a retrofit measures to the maintenance intervention. In addition to these considerations, long-term analyses are highly sensitive to discount rates (García-Gusano et al., 2016). With a lower discount rate, the cost-optimal curve is shifted toward higher investment paths (left part of Figure 5-11), but the obtained investment type results consistent. This can suggest interest rates are another powerful way of promoting building retrofit. Furthermore, *"Considering the actual fiscal policies for energy renovation in Italy (tax detraction, (Nocera, 2015)), the cost-optimal range is shifted to lower values of energy demand (8 and 14 kWh/m^3) and lower cost (37 and 56 €/m^3). Anyway, for the structure of the actual fiscal policy (tax detraction for an investment lower of a fixed upper cap), aggressive intervention on SF are advantaged with respect to the renovation of bigger buildings where usually investments are much higher than the maximum economic incentive*" (Delmastro et al., 2016a).

To conclude, this section applied the cost-optimal analysis to identify a suitable range of cost-effective range of space heating intensities to be promoted across an urban building stock. This supports the selection of the measures used for performing the scenario analysis in further sections and chapters.

5.3.1.4. Generation urban building energy scenarios

Scenarios analysis allows investigating and comparing the impact of different alternatives over a fixed time-horizon and under certain user-defined assumptions. Even if unpredictable changes cannot be captured in the analysis, scenarios still represent an opportunity to provide indications about the future and to choose between different policies (e.g., energy policies, fiscal policies, renovation measures etc.). In this thesis, scenarios analysis is adopted to understand possible trends of space heating end-use savings and consumption patterns to 2050 by considering retrofit policies identified through the cost-optimal analysis. In this research, the renovated volume, disaggregated for each building type, was calculated as in Eq. (2).

$$\mathrm{V_{Ren,TOT}} = \sum_{\mathrm{j}} \sum_{i}^{n} \left[\mathrm{V_{Ex,TOT,i}} * \mathrm{t_i} * \mathrm{r_{i,j}} \right] \qquad (2)$$

where:

$V_{ren,TOT}$ is the total retrofitted volume in 2050 (m^3); j is the RB type; i is the step of time period (4 time periods from 2015 to 2050); $r_{i,j}$= renovation rate of building type j in the time period i ;$V_{ex,TOT}$ is the existing not renovated volume at the beginning of the time step *i*; t_i is the numbers of years within the *i* time period; and n is the total number of time periods (equal to 4). The considered urban volume is 100 Mm^3 of which 57 Mm^3 connected to the district heating and 43 Mm^3 heated by gas boilers (in 2015).

Three building scenarios are proposed considering three different retrofit packages, for each RB, with different penetration (annual retrofit) rates (Table 5-4). The Baseline (B) scenario takes into account the current renovation trends and is assumed to achieve 10% energy; the Moderate (M) and Advanced (A) scenarios refer to measures selected from the cost-optimal analysis and assume building energy savings of at least 30% to 50% with annual application rates of 2% to 3%, respectively.

Table 5-4. Building scenarios. From (Delmastro et al., 2017a, 2017b).

Scenario Name	Scenario description
Baseline (B)	1% annual renovation rate of measures allowing 10% energy savings (e.g. window substitution)
Moderate (M)	2% annual renovation rate of measures allowing 30% energy savings (e.g. new insulation)
Advanced (A)	3% annual renovation rate of measures allowing 50% energy savings (e.g. new insulation, thermostatic valves)

Due to presumed market constraints, the Moderate and Advanced scenarios assume measures that are spread starting from 2020 and, depending on the retrofit rates, follow different evolution paths. The evolution of the renovated building volume and the evolution of space heating energy intensity of buildings network can be observed in Figure 5-12.

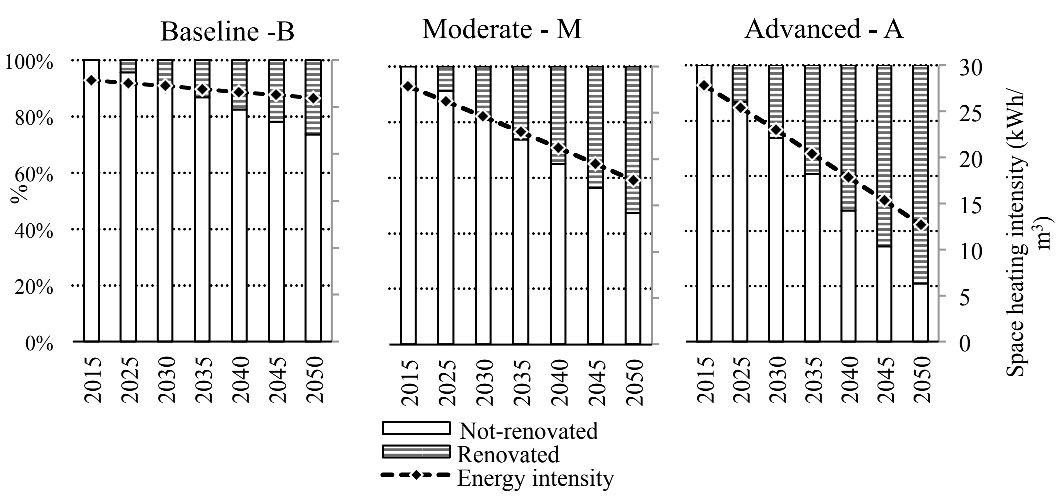


Figure 5-12: *Evolution of building volumes and space heating intensity under three different scenarios.* (Delmastro et al., 2017b).

Eq. (3) evaluates the global cost (2015-2050) associated with each building scenario ($C_{G,BS}$). The 2050 global cost is discounted at 2015 levels and its evaluation includes O&M costs, fuel cost and new investment costs for retrofit interventions. The fuel cost associated with district heating consumption is not included since it is evaluated in the DH model (Section 5.3.2). The cost related to new buildings is not considered since it is equal in all the scenarios.

$$C_{G,BS} = \sum_j \sum_{i=1}^{n} \left[C_{INV,i,j} + (O\&M_{a,j} + C_{e,d,j}) * t_j - RV_{i,j} \right] * d_i \qquad (3)$$

Where j is the building archetype; i is the step of the time periods; n is the total number of time periods (4 time periods from 2015 to 2050); $C_{INV,i,j}$ = investment cost occurred related to the archetype *j* in the time period *I*; $O\&M_{a,j}$ is the yearly O&M cost for the archetype *j* in the time step *I*; $C_{e,d,j}$ is the fuel cost relative to the building archetype *j* in the time period *I*; ti = number of years of the time period *i*; $RV_{i,j}$ is the residual value of the investment occurred in the time period *i* for the building archetype *j;* and d_i is the present value factor for the mid-year (2.5, 7.5, 12.5, 32.5) of each time period *i* (assumed discount rate of 3.5% above inflation).

5.3.2 Heat generation and delivery

This section describes the developed model for simulating the evolution of the district heating generation mix and its behaviour over long-term horizons. The model also accounts the individual heat boilers stock and allows generating scenarios about its evolution (replacement with heat exchangers, new boilers, etc.). The model was developed in cooperation with the International Energy Agency, Politecnico di Torino and the Swedish Environmental Research Institute (IVL)(Delmastro et al., 2017a). It simulates the operation of district heating systems capturing the impact on heat production costs of: (i) space heating demand variations, (ii) network expansion possibilities and (iii) investment in new capacity.

In 2015, 57 Mm^3 of the urban building volume was supplied by an entirely gas-based district heating system managed and operated by a single company, where there are still possibilities of expanding the network (Guelpa et al., 2017). The heat generation mix is composed by 740 MW of natural gas CHP, 1000 MW of gas auxiliary boilers and 12,500 Mm^3 of daily storage delivering about 2000 GWh_{th} together with 950 GWh_{el} (Gruppo IREN, 2015). The buildings that are not connected to the district heating network are mostly supplied by natural gas boilers (more than 80%), some fuel oil boilers (~11%) and electricity (~3%). In this specific application, as previously specified, a boundary of 100 Mm^3 was considered of which 57 Mm^3 are already connected to the DH network while 43 Mm^3 are heated by traditional gas boilers and may be potentially connected to the DH network or supplied by other distributed technologies (e.g., heat pumps, modern biomass boilers, condensing-gas boilers, micro-CHP). This last option wasn't then exploited for the scenarios development to maintain the attention on district heating and to keep the scenarios as understandable as possible; the competition among district-heating and distributed generation will be further explored in Chapter 6.

The time resolution of the DH model is on an hourly level over a one-year time period. This model was built to combine the annual results into medium-long term scenarios: a simulation over 35 years was made to explore different scenarios to 2050 (time horizon 2015-2050) and, for computational reasons, the time-horizon was divided into 4 time periods (the first one lasting for 5 years and the others lasting for a decade).

The base-year input of the model are: (i) the hourly load curve of the existing network relative to two representative years, respectively a cold and a warm year and (ii) the techno-economic data of the existing generation mix (plant capacities, efficiencies, power to heat ratio (for CHP) and emissions factors). The evolution of the load curve is distinguished between residential and non-residential heat profiles. The residential thermal load is further divided into space heating and domestic hot water (minimum summer heat load assumed as domestic water heating). The focus of this thesis is the evolution of space heating loads; all the other energy services profiles remain constant. The other required input is referred to the evolution of the heat generation capacity and network expansion and the related techno-economic information. On this last input (evolution of heat generation capacities and the relative costs), scenarios can be built up. In the cost calculation, the model takes into account dynamic variations in distribution losses accordingly to the average line density function derived from data in (Svensk Fjärrvärme, 2007), the variable and fixed O&M costs, the fuel cost, the electricity produced by CHP plants, carbon taxes and any new investments. All the investment and operation costs consider commercially available technologies and the current energy prices in Italy.

*"The main **outputs of the model are the hourly heat production costs for each technology**. According to the load diagram and the hourly heat production costs, the model sorts the heat generation capacity in merit order (activating first the plant with lowest variable operating cost followed by the second lowest operating cost and repeating the sequence until the last most expensive plant - usually peak plants - is brought online) (Frederiksen and Werner, 2014). In this way, it is possible to catch the effects of new investments and space heating*

demand reduction on the heat production cost (Figure 5-13). Even if the effect is not directly captured, it is clear that demand reduction would save not only energy but also necessary capacity and could, therefore, have unintended implications for investments in new DH generation capacity". (Delmastro et al., 2017a).

The co-generated electricity from CHP plants is supposed to be equivalent to that of electric power plants and therefore it is assumed that if this electricity had not been produced by CHP, it would have been produced elsewhere, considering the current and future electricity production mix. The electricity price in 2015 is fixed to 50 €/MWh (Comodi et al., 2017). Moreover, a carbon tax that grows from 16 $€/_{tCO2}$ in 2015 to 141 $€/_{tCO2}$ in 2050 (International Energy Agency, 2016) was included in the evaluations. The carbon tax was included to push forward renewable heat options in a reality that is almost 100% supplied by natural gas.

Consequently, the yearly levelized cost of heat LCOH can be derived by applying Eq. 4.

$$\mathrm{LCOH}_i = \frac{\mathrm{C_i} * \mathrm{d_i}}{\mathrm{E_{dhtot,i}}} \qquad (4)$$

Where i is step of the time periods (4 time periods from 2015 to 2050); C_i is the yearly fuel cost, running and fixed O&M for the plants, O&M for the distribution network, connection costs relative to time period *i*; d_i is the present value factor for the mid-year of each time period (calculated as in Eq. 3); and $E_{dhtot,i}$ is the delivered heat from DH during each year of the time period *i*.

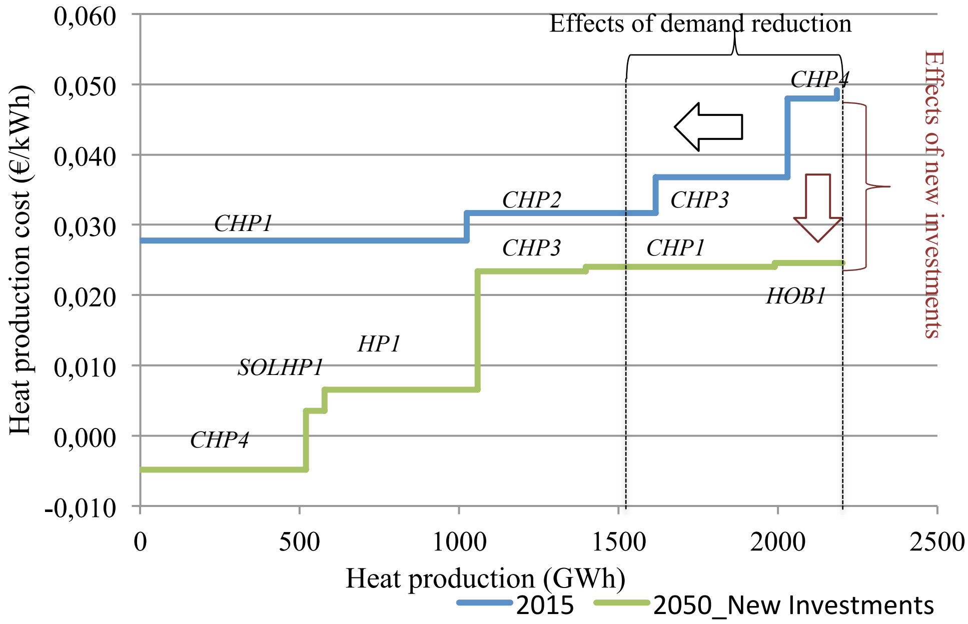


Figure 5-13: Example of the effects of new investments and demand reduction on the heat production cost. *CHP4, SOLHP1 and HP1 are an example of new investments respectively a waste CHP, solar thermal plants coupled with heat pumps and heat pumps.(Delmastro et al., 2017a).

The global cost to produce and supply heat is evaluated through Eq. 5.

$$C_{G,dh} = \sum_{i=1}^{n=4}(LCOH_i * E_{dhtot,i} + C_{INV,dh,i} * d_i) \qquad (5)$$

Where i is the step of the time periods; $C_{G,dh}$ is the total discounted life-cycle cost of the DH system; $LCOH_i$ is the discounted levelized cost of heat up to the mid-year of each time period i; $E_{DHtot,i}$ is the heat delivered to the users during *i* time period; $C_{INV,dh,i}$ is the investment costs in new DH capacity during the time step *i;* and d_i is the present value factor for the mid-year of each time period (calculated as in Eq. 3). Furthermore, the model calculates the equivalent CO_2 emissions $CO_{2,eq,dh,tot}$ (t) to 2050, including the emission factor of methane (CH_4) and nitrous oxides (N_2O) that are respectively equal to 23 kg_{CO2}/kg_{CH4} and 296 kg_{CO2}/kg_{N2O} , with respect to the operation of the DH system as Eq. 6.

$$CO_{2eq,dh,tot} = \sum_{i=1}^{n=4}((\sum_{j=1}^{n=8760}(\sum_{x=1}^{n} CO_{2,eh,x,j} * E_{plant,x,j}))/E_{dhtot(j)})_i * E_{dhtot,i} \qquad (6)$$

Where *i* is the step of the time periods; *j* is the hour of the year; *x* is the DH plant; $E_{dhtot,\ i}$ (kWh) is the heat delivered to the users during *i* time period; $CO_{2,eh,xj}$ (t/h) are the equivalent carbon emissions from heat plant *x* in hour *j*; $E_{plant,x,j}$ (kWh/h) is the heat produced from plant x in hour *j* considering the merit order of plants, the demand variation and the availability of the plant; and $E_{dhtot(j)}$ (kWh) = total yearly delivered heat. No variation in the electricity-to-heat quota was been considered.

For this thesis, three different scenarios involving DH investments are generated (Table 5-5). Technologies were selected by considering local utility plans (interactions with the local utilities to share the vision), existing network and technology characteristics, relevance for future policies, available land area for renewable energy sources and resource availability. This is necessary for proposing realistic and feasible (technically and economically) options for each municipality. The technology heat capacities were defined taking into account the thermal demand to be supplied in the time periods, the commercially available capacities and the available space for renewables.

Table **5-6** summarizes the main characteristics of the selected technologies. The resulting technological choices (not always all activated, depends on the network expansion) are:

- Moderate (M) scenario: 260 MW of existing gas CHP replaced by a CHP (106 MW - already planned) fuelled by refused derived fuel, heat pumps (5 MW – considering the presence of a river) and a gas-based CHP (150 MW – following existing gas-based trend) were progressively simulated.
- Advanced (A) scenario. Toward a low carbon vision, this scenario plans a decommissioning of 260 MW of existing gas CHP to be progressively replaced by a CHP (106 MW - already planned) fuelled by refused derived fuel, heat pumps (250 MW) and solar thermal heat plant field (11 MW – considering land availability) with borehole seasonal storage.

To these technological options, three network expansion options can be coupled: 11 Mm^3, 30 Mm^3 or 43 Mm^3.

Table 5-5. District heating scenarios. (Delmastro et al., 2017a).

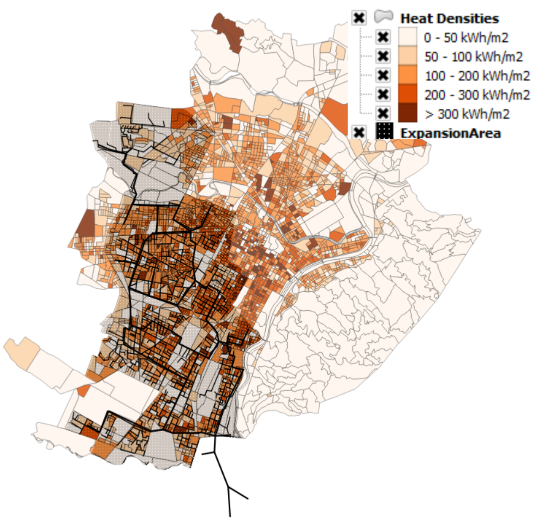
Investment scenarios	
Baseline B	*Actions:* Regular O&M
Moderate M	*Actions:* investments in 1 unit of 106 MW CHP fueled by refused derived fuel (2020); 5 MW of heat pumps (2025); 150 MW of gas CHP (2030) Decommissioning of 260 MW of existing capacity (2025)
Advanced A	*Actions:* investments in 1unit of 106 MW CHP fueled by refused derived fuel (2020); 250 MW of heat pumps (2025); 11 MW of solar thermal heat plant fields with multiple borehole seasonal storage and heat pump (2030) (Tonhammar, 2014) Decommissioning of 260 MW of existing capacity (2025)
Network expansion options	
	*Network expansion:* three network expansion options are considered: *11 Mm^3, ** 30 Mm^3, ***43 Mm^3. (expansion area=black area)

Table 5-6. Main characteristics of selected technologies. (Delmastro et al., 2017a).

*fuel costs refer to national market values and the evolution of fuel costs was set in order to follow the trend of the IEA World Energy Outlook (IEA (International Energy Agency), 2013).
**life of technologies, variable O&M and investment costs refer to private databases. Fix O&M was set equal to 3% on initial investment costs.
***average values are reported per MWh of delivered heat from the plant, emission factors are calculated by the model considering the operation of the power plants, the alternative production method is used to allocate the emissions to electricity and heat in CHP-plants, emissions factors for fuels are used from (Gode et al., 2011).

Utility plant	Heat Capacity [MW_{th}]	Heat to Power Ratio	Efficiency (%)	Auxiliary electricity (% of gross electricity)	Lifetime (years)**	Emission factors ($kg_{CO2,eq}$/MWh)***
Natural gas CHP (existing)	2*260 1*220	0.31-0.57	88%-82%	3%	25	123-147
Natural gas HOB (existing)	2*250 1*140 1*45	-	95%-92%	0.5%	35	215-228
Daily storage unit (existing)	1*130 (2500 m3) 2*150 (5000 m3)	-	-	0.5%	15	-
RDF CHP unit (new)	106	0.3	70%	3%	25	51
Heat pumps (new)	5 (M)/ 250 (A)	-	3 (COP)	0.5%	20	92
Solar thermal heat plant (new)	11	-	70%	5%	30	4

5.3.3 Integrating demand and supply

To assess the proposed scenarios, the variation of the urban space heating requirements generated by building renovations (Section 5.3.1) is used as one of the inputs of the DH simulation model (Section 5.3.2). An integration module was created to assess costs, energy savings and emissions from both the buildings model and the DH model with the aim of calculating the total system cost (TSC), which includes the cost associated to individual heat generation options, and the associated emissions reduction for the various combinations of buildings and DH scenarios. In this section, the basic concepts behinds the integration module and the proposed scenario analysis are presented.

The total system cost (TSC) to 2050, discounted at 2015 levels, is therefore evaluated as (Eq.6), as the sum of the building costs (Eq. 3) and to the heat generation system (Eq.5).

$$TSC = C_{G,dh} + C_{G,BS} \quad (6)$$

Where TSC is the total discounted life-cycle cost considering the total cost of buildings $C_{G,BS}$ referred to 2050 discounted at 2015 level as Eq. 3 and the total cost of the DH network $C_{G,dh}$ to 2050 discounted at 2015 level as Eq. 5.

The total equivalent carbon emissions to 2050 $\left(CO_{2,tot}\right)$ are consequently evaluated as the sum of the emissions derived from the heat production from DH system and from independent heat production (Eq. 7).

$$CO_{2eq,tot} = CO_{2eq,dh,tot} + CO_{2eq,b,tot} \quad (7)$$

Where $CO_{2eq,dh,tot}$ are the carbon equivalent emissions to 2050 related to DH production, and $CO_{2eq,b,tot}$ are the CO_2 equivalent emissions to 2050 related to the heat production at the building level (not connected to the DH network, but heated by individual gas boilers). Nine scenarios were created for combining building scenarios together with DH scenarios. They combine progressive intervention on buildings side together with progressive intervention on DH side (Table 5-7):

- The Baseline BB* scenario represents the condition in which no significant new investments are planned.
- Scenarios Uncoordinated Moderate Buildings MB* and Uncoordinated Advanced Buildings AB* represent the situation in which the new investments in buildings are not coordinated with DH strategies.
- Scenarios Uncoordinated Moderate Heat BM* and Uncoordinated Advanced Heat BA* simulate the opposite condition in which all the new DH investments are not coordinated with building strategies.
- All the remaining scenarios (Coordinated Moderate MM**, Coordinated Advanced Buildings AM*, Coordinated Advanced Heat MA**, and Coordinated Advanced AA***) represent progressive combinations of buildings and DH strategies.

Table 5-7. Scenario matrix. (Delmastro et al., 2017a; International Energy Agency, 2016). Expansion for Torino: *11 Mm^3, ** 30 Mm^3, ***43 Mm^3.

		BUILDINGS SCENARIOS (Section 5.3.1)		
		Baseline	Moderate	Advanced
DISTRICT HEATING SCENARIOS (Section 5.3.2)	Baseline	Baseline - **BB***	Uncoordinated Moderate Buildings - **MB***	Uncoordinated Advanced Buildings - **AB***
	Moderate	Uncoordinated Moderate Heat - **BM***	Coordinated Moderate - **MM****	Coordinated Advanced Buildings - **AM***
	Advanced	Uncoordinated Advanced Heat - **BA***	Coordinated Advanced Heat - **MA****	Coordinated Advanced - **AA*****

5.4 Results

The principal results are summarized at first by looking at three indicators: energy savings, emission reduction and total system costs (TSC) (Figure 5-14 and

Figure 5-15). The TSC is further disaggregated into fuel cost, operation and maintenance costs, building investments (retrofit) and district heating investments (new capacity plus network expansion). All the indicators are compared to the ones of the Baseline (BB*) scenario.

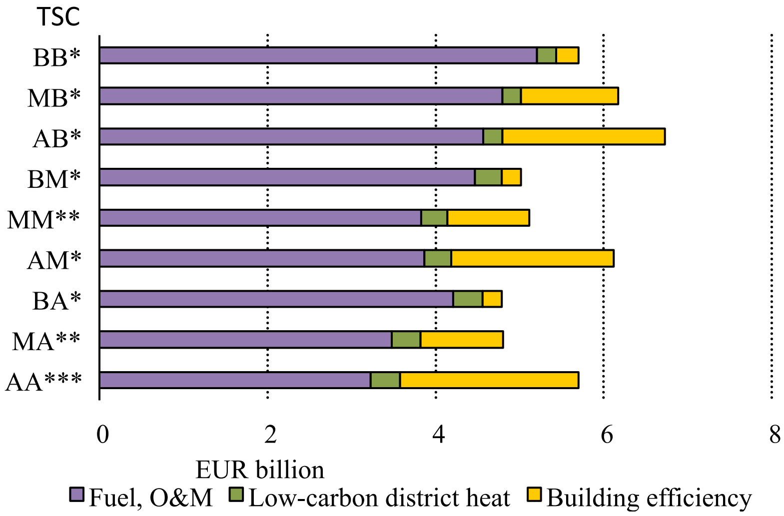


Figure 5-14: Results of the scenarios analysis in terms of total system cost (TSC) discounted at 2015 levels. Expansion for Torino: *11 Mm^3, ** 30 Mm^3, ***43 Mm^3. Adapted from (Delmastro et al., 2017a; International Energy Agency, 2016).

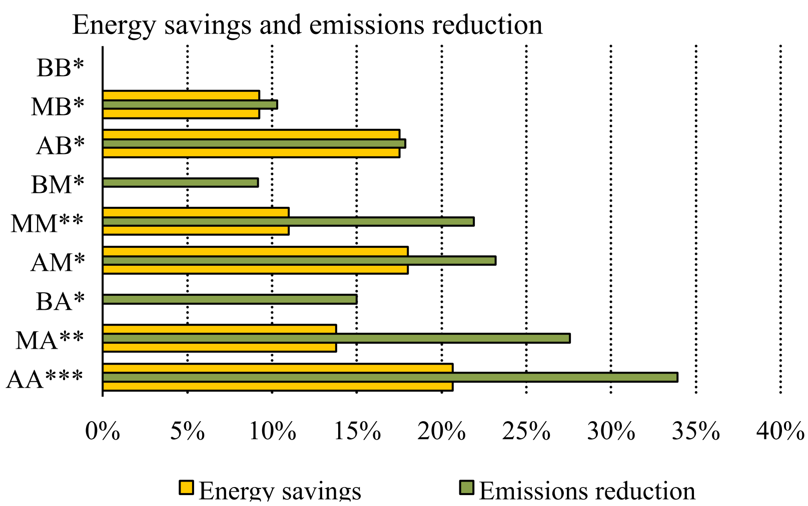


Figure 5-15: Results of the scenarios analysis in terms of energy and emission savings. Expansion for Torino: *11 Mm^3, ** 30 Mm^3, ***43 Mm^3. Adapted from (Delmastro et al., 2017a; International Energy Agency, 2016).

Results are summarized for:

- Building retrofit not coupled with district heating strategies: scenarios Uncoordinated Moderate Buildings - MB* and Uncoordinated Advanced Buildings - AB* lead to higher total system costs compared to Baseline - BB*, respectively by about 8% and 18%. In these scenarios retrofit investments are not offset by the reduction of operational costs: fix costs remain the same, the network is not expanding and the heat production is considerably lower to its capacity. Compared to Baseline, the reduction of carbon emissions is close to 10% for Uncoordinated Moderate Buildings MB* and to 20% for Uncoordinated Advanced Buildings - AB*.

- District heating investments not coupled with retrofit intervention: Scenario Uncoordinated Moderate Heat BM*, which takes into account moderate investments in the DH system, allows reducing the TSC by 12% compared to Baseline - BB* (reduction of operation and O&M costs) with $CO_{2eq,tot}$ savings similar to scenario Uncoordinated Moderate Buildings MB*. Scenario Uncoordinated Advanced Heat BA* may be beneficial in terms of emissions reduction of 15% (Figure 5-16) while maintaining a reduction of TSC of 16% compared to Baseline - BB*.
- District heating investments coupled with retrofit intervention: Scenario Coordinated Moderate MM** adds Moderate investments in building retrofit coupled with network expansion and new heat capacity investments. The TSC decreases by about 10% with more than double the carbon emissions reduction compared to Uncoordinated Moderate Heat BM*. In this scenario, fuel cost savings (lower heat demand plus improved efficiency of the generation mix) are higher with respect to the sustained investments. Environmental benefits depend on reduced fuel consumption, new generation mix and the phase-out of inefficient existing gas boilers. Further and deeper building retrofit measures (scenario Coordinated Advanced Buildings AM*) without expanding the DH network cause an increase, with respect to Baseline, of the TSC by 7% while the carbon emissions reduction is not significantly higher compared to Coordinated Moderate MM** (+1%). This scenario highlights that district heating strategies require finding synergies with retrofit measures in buildings. Further district heating low-carbon investments are added in scenarios Coordinated Advanced Heat MA** and Coordinated Advanced AA***. Scenario Coordinated Advanced Heat MA** roughly reach the same TSC of scenario Uncoordinated Advanced Heat BA*, but with higher emissions reduction (28%). Interestingly, scenario Coordinated Advanced AA*** represents investments limit for maintaining the same level of TSC cost with respect to the Baseline. Noticeably, even if this scenario has higher emissions reduction (34%), the benefits of reducing the demand of buildings start to diminish. Going further would imply investments that are not offset by economic savings, even if technically feasible.

To sum up, scenarios Coordinated Moderate MM**, Coordinated Advanced Heat MA** and to some extent Coordinated Advanced AA***, representing synergies in both building retrofit and the DH system, lead to the best combination of TSC and carbon emissions reduction. The choice of the strategy depends on the willingness to invest relative to achieving the emissions target. Nonetheless, all the scenarios, excluding Uncoordinated Moderate Buildings MB*, Uncoordinated Advanced Buildings AB* and Coordinated Advanced Buildings AM*, can contribute reducing both TSC and carbon emissions, at different levels. The main strengths of these scenarios are represented by their capability to reduce fuel combustion for heat production, thanks to a decrease in peak and total thermal demand. In the specific context of Torino, a reduction in peaks would also allow a significant reduction in heat production from low-merit order power plants (already rarely used in 2015).

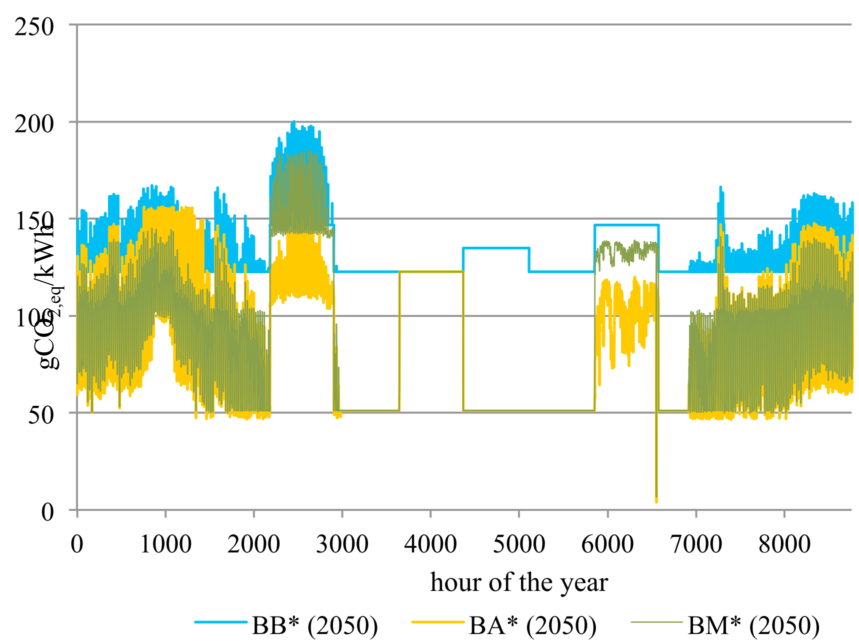


Figure 5-16: Hourly emissions ($gCO_{2,eq}$/kWh) under different scenarios in Torino. (Delmastro et al., 2017a).

Moreover, when the building retrofit is coupled with the expansion of the network, the benefits of maintaining heat production levels closer to heat output capacity can be particularly observed since the system highly relies on CHP units. By looking at the level of carbon emission reductions compared to 1990, all the scenarios allow reaching more than 40% emission reduction in 2030 meaning that the heat generation park of the city is already efficient (most of DH relies on CHP). In able 5-8 is possible to observe how the scenarios behave with respect to environmental 2050 targets (compared to 1990 levels): scenarios identified as the best combination of measures (Coordinated Moderate MM** and Coordinated Advanced Heat MA**) are very close to a 70% emission reduction, still lower to the European 80% target only reached by the limit scenario Coordinated Advanced AA***. In addition, the table summarizes the main results by grouping the scenarios according to the TSC and emission savings showing that: (i) some scenarios involve deep building retrofit without gaining a significant reduction of operational costs: MB*, Uncoordinated Advanced Buildings AB*, Coordinated Advanced Buildings AM* cause district heating plants to produce much lower to their capacity and require further network expansion; (ii) some scenarios involve a change in the heat supply mix: Uncoordinated Moderate Heat BM*, Uncoordinated Advanced Heat BA* allow a CO_2 emission reduction greater than 50%, but in the specific context of Torino it is not sufficient to reach 2050 environmental targets; by looking at the "green" scenarios Coordinated Moderate MM**, Coordinated Advanced Heat MA** and Coordinated Advanced AA***, the key message is that the best combination involves a reduction of fuel combustion for heat production, a decrease in peaks and total thermal demand coupled to a network expansion to guarantee a district heat production level closer to heat output capacity.

able 5-8. CO_2 emission reductions compared to 1990 levels. Square: no combination of investments; Circle: combination of investments across building renovation and district heating investments; Green: total system costs lower than Baseline BB*; Red: total system costs greater than Baseline BB*.

		BUILDING SCENARIOS		
		Baseline	**Moderate**	**Advanced**
DH SCENARIOS	**Baseline**	**44.9% CO_2 emission reduction** BB*	**58.2% CO_2 emission reduction** MB*	**72.6% CO_2 emission reduction** AB*
	Moderate	**50.2% CO_2 emission reduction** BM*	**68.5% CO_2 emission reduction** MM**	**73.5% CO_2 emission reduction** AM*
	Advanced	**52.2% CO_2 emission reduction** BA*	**75.2% CO_2 emission reduction** MA**	**82.8% CO_2 emission reduction** AA***

Investments in buildings not offset by reduction of operational costs; DH heat production lower to its capacity

Best combinations of interventions: the choice depends on the willingness to invest and on environmental targets

Investments in supply are always beneficial, but not sufficient to reach environmental targets in this specific context

5.5 Discussion

From the proposed scenarios analysis it can be observed that, in some cases, consistent heat savings may not be a cost-effective approach if additional demand by network expansion cannot be used to fully utilise DH capacity. Retrofit interventions should be planned with attention not to significantly decrease the use of the existing base load plants. Variation of the heat profile would also change the size of new investments for base load plants, and so new capacity should be planned carefully with respect to anticipated building measures. Consistent new DH investments require building retrofit measures to be cost-effective, properly planned and matched with respect to strategies for new DH capacity and possible network expansion. Building retrofit has positive effects when allow shifting away the utilization of low-merit order power plants. Yet, a high utilization of base load capacity should be maintained for guarantying cost-effectiveness of DH systems. This is clearly easier in areas in which a further expansion of the DH network to counterbalance energy savings is feasible. Understanding the expansion potential of existing DH systems (e.g., through heat mapping) is, therefore, a challenge for proposing future heat strategies.

The presented methodology enables explorative scenarios to understand their impacts on the energy system with respect to important economic and planning considerations. This approach already requires knowing the configuration of the local energy system as well as the technologies that would be taken into account. A wide range of scenarios may, therefore, be further proposed to improve and enhance the analysis: additional technologies and further specific assessments can help to refine the conclusions explained in this Chapter. The combinations of the described technologies may be extended in further analyses, possibly requiring other iterations to be discussed with local decision makers. Nevertheless, this approach already provides in the first instance a useful indication to assessing prospective pathways forward for integrated building and district energy solutions to deliver a first-level assessment of the appropriate combination of measures within a more integrated energy system planning. A complement of the presented methodology is presented in Chapter 6 where an optimisation framework across multiple competing technologies is proposed. Using those types of approaches, while typically more complex and resource demanding, could provide greater insight into the configuration of the energy system with respect to investments, life-cycle costs and environmental targets (e.g., emission reductions).

5.6 Conclusions

In this chapter, a methodology for exploring the impact of building retrofit policies on the operating conditions and investment strategies for DH networks, and more broadly for heat generation, is presented. A matrix of scenarios, involving progressive investments in building retrofit coupled with progressive investments in district heating, is generated to understand their impacts on the energy system by looking at three main indicators: the total system cost, energy savings and carbon emission reduction. From the presented results, it is emphasized the specific need in district heated cities to re-think current building retrofit policies to support the progressive decarbonisation of the supply sector (e.g., utility companies may propose building renovation measures coupled with new connections to DH networks). The main advantage of the proposed method is its capability to scale up the perspective from a single building level to an energy system level, capturing the interdependencies between supply and demand that are traditionally treated individually in urban planning applications. In particular, this may lead to DH business strategies and urban energy plans that avoid unnecessary investments.

The central role of finding synergies between energy saving measures and new investments in the heat supply mix in Europe, and in particular in cities with DH is stressed here. In fact, from results emerged that beyond certain levels of demand reduction, the economic benefits of building retrofit start to decrease and in some cases may not be cost-effective (when the heat output is much lower compared to installed capacity). The possibility of coupling DH network expansion with building retrofit may allow DH systems to operate with sufficient utilisation factors of the base load plants. This condition is not always possible for many reasons, including network saturation and urban constraints and barriers (e.g., historical built environments).

The proposed methodology does not seek to replace existing energy systems modelling approaches, but rather it aims to provide an integrated framework to provide a more informed assessment of the appropriate investments for buildings and DH networks with respect to each other, their life-cycle costs and energy and environment ambitions. It is flexible and extendible to other urban areas and can be coupled with other integrative methodologies. Further work (Chapter 6) will address the study of the competition between different technologies (e.g., expansion of DH or use of stand-alone heat pumps) and sensitivity analyses on energy prices.

Chapter 6

Detailed energy modelling phase: optimization approach

6.1 Overview

This chapter presents an urban energy system optimization model with original features in order to study the specific interactions between energy efficient buildings and the development of urban heat strategies (Figure 6-1).

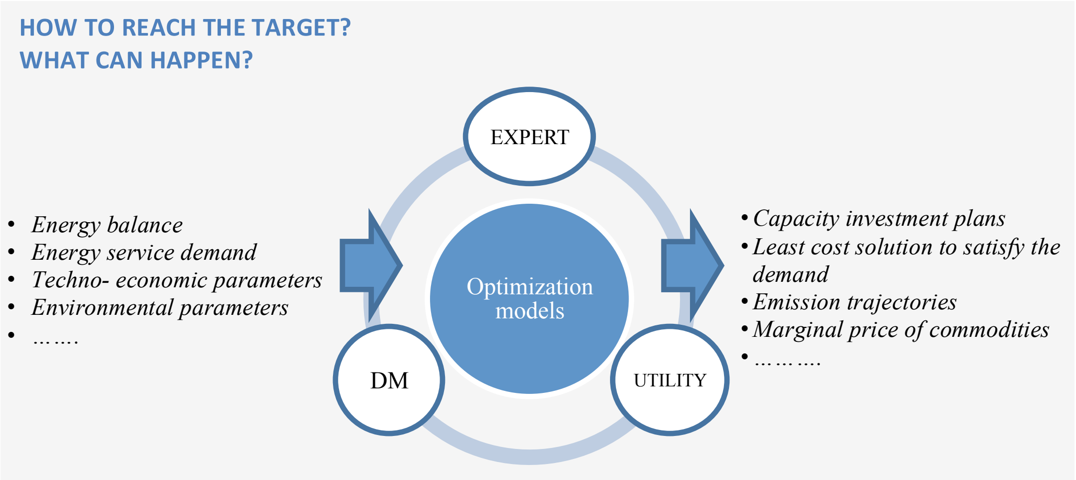


Figure 6-1: Schematic of energy system optimization models.

Key findings:

Methodology:

- The proposed approach is suitable for assisting the development of medium/long-term energy plans at an urban scale (prescriptive investment optimization), supported by a dynamic optimization over the whole time horizon.
- This approach is particularly suitable for thermal analyses in which commodities can be easily stored, reducing the limits connected to a low time resolution.
- Great attention is required to input data and uncertainties, in particular for an accurate description of starting Reference Energy System and innovative technologies not yet market ready that tends to be excluded considering the high upfront costs.
- A spatial representation of the urban environment helps better understanding the retrofit potential and evaluating territorial constraints. It facilitates the localization of measures according to social, technical and territorial evaluations.

Case study:

- To reach a high decarbonisation level, a portfolio of demand reduction, higher efficiency technologies and higher share of renewable is required.
- Results confirm that deploying building retrofit together with low carbon technologies can reduce the environmental impacts at a reasonable added cost..
- Even if the diffusion of building retrofit may be limited by high upfront costs, it is consistently selected to reduce the costs for decarbonization. This also reduces the dependency from a decarbonized power sector, opening new research on the possibility of greening the gas network for a low carbon transition.
- An increased electrification in end use services is driven by the reduction of thermal needs and a slight increase of electricity demand (space cooling), such as through heat pumps covering parts of the thermal demand and a decarbonized power sector.

Key limitations:

- The model cannot catch the dependency of DH network and variations in linear heat density.
- The low time resolution may underestimate electricity peaks and the mismatch between energy demand and energy production.
- Not all the necessary urban data were available, requiring the need of improving data gathering capacity. This will require the involvement all urban stakeholders.
- Local pollution was not accounted and targeted, even if crucial in urban applications, since the mobility sector is not modelled.

Declarations.

Part of the work described in this Chapter has been submitted to the Journal “Energy”.

6.2 Introduction

This chapter focuses on the use of scenario tools/models that "*usually combine a series of years into a long- term scenario*" and "*function in time-steps of 1 year and combine such annual results into a scenario of typically 20–50 years*" (Connolly et al., 2010). This approach allows proposing "explorative" and "normative" scenarios of how the system could evolve (Börjeson et al., 2006). It can be very helpful for supporting the choice among several optimized "medium/long-term" investment strategies. Although, scenario tools and models have mostly been adopted for large-scale applications and their possible adoption for local applications has been tested in recent years only. The rising interest in local scenario tools is driven by their capability to catch the long-term energy and economic interactions between the different systems. Some of the very few urban examples are represented by the study of (Jennings et al., 2014) in which a linear programming approach was applied to support urban stakeholders in their choice among several building technologies in London. One of the latest application consists in the InSmart Project (InSmart, 2015) in which the TIMES model generator (Loulou et al., 2005) was chosen as energy planning tool for shaping urban energy plans. Another recent urban application of the TIMES model was proposed in Oslo by (Lind and Espegren, 2017) for finding the optimal way of reducing CO_2 emissions and energy consumption. To the best of the authors' knowledge, even if scenario tools have been recently adopted for local analyses, any TIMES urban model has been structured with the specific focus of finding the possible synergies between building renovation and heat strategies including DH investments or expansions. To this extent, considering that the modelling frameworks of scenario tools were typically focused on the supply side while urban analyses require greater details on the end-uses, great attention needs to be devoted to taking into account local context peculiarities and demand disaggregation. This chapter presents an urban energy system optimization model with original features in order to study the interactions between energy conservation in buildings and the development of urban heat strategies. Compared to the simulation approach (Chapter 5), an optimisation framework takes into account the competition across multiple technologies. Compared to Chapter 5, this model extends the analysis to the whole city, to all building services and the related technologies to supply them. It provides, therefore, a broader perspective of heat decarbonization options. In fact, the goal of the Chapter is to develop a comprehensive energy-planning model that integrate demand and supply and guarantee a complete representation of the built environment energy system with a suitable demand disaggregation level.

As explained in Chapter 3 and Chapter 4, the choice of the TIMES model generator is justified by its structural flexibility that allows the users to define, according to his needs, the technological and temporal resolution of the model. The proposed modelling approach allows to interact with other methodologies (f.i. building simulation, Geographic Information Systems GIS) and to integrate information across different scales in order to disaggregate the building sector by destination use and building type. Moreover, the TIMES urban model is explicitly structured in order to deliver the necessary spatial and temporal resolution for tackling the specific question of building renovation impact on heat strategies. In this Chapter, the model resolution is shaped according to the data availability Torino.

Section 6.3 describes the base year reference energy system and explains the methodology. The analysed scenarios and the principal assumptions are described in Section 6.3.7. Section 6.4 presents the results and Section 6.5 is dedicated to the discussion. Conclusion remarks are summarized in Section 6.6.

6.3 Methodology

In this section, the structure of the Torino-TIMES model is described. The base year of the model is set to 2015 and model time horizon is from 2015 to 2050 (referring to EU environmental targets). The building sector is defined in order to disaggregate the building environment in Reference Buildings RBs per destination use. This specific choice is driven by the necessity of studying the interactions between specific building retrofit alternatives and future urban heat strategies. The methodology section is divided into 7 independent subparagraphs dedicated to the description of the RES, its main components and the principal adopted assumptions. All the new technologies progressively replace the existing ones and compete in order to satisfy the energy service demands. As it is clear from the whole thesis, the available urban data are not temporally homogeneous. The model was therefore calibrated taking into account the available 2005 energy balance (Città di Torino, 2012), the total district heating load in 2014 (Delmastro et al., 2017a; Gruppo *IREN,* 2015) and recent analysis on building volumes distribution (Mutani et al., 2016).

6.3.1 Overview of the Reference Energy System

The first modelling activity is represented by the definition of the RES. Its structure is outlined by taking in mind the targeted demand sectors, the commodities to be further modelled and the main characteristics of the area.

The base-year (2015) structure of the RES relies on the energy balance of the local contest (Città di Torino, 2012) in order to define and quantify, from a top-down perspective, the consumed resources per sector. Secondly, bottom-up punctual analyses to characterize the demand profiles of buildings were performed with the support of GIS tools, real energy consumption data and building modelling (as described in Chapter 5). By means of this last step, the level of demand disaggregation and time-periods were defined. As can be observed in Figure 6-2, the RES is divided into five main sections from primary sources to final uses: Primary Energy Supply and Imports (Section 6.3.3), Conversion sector (heat generation) (Section6.3.4), Transport and Distribution Options (Section 6.3.5), End-use technologies (Section 6.3.6) and Demand Sectors (Section 6.3.2). A complete vision of the RES is provided in Annex B.

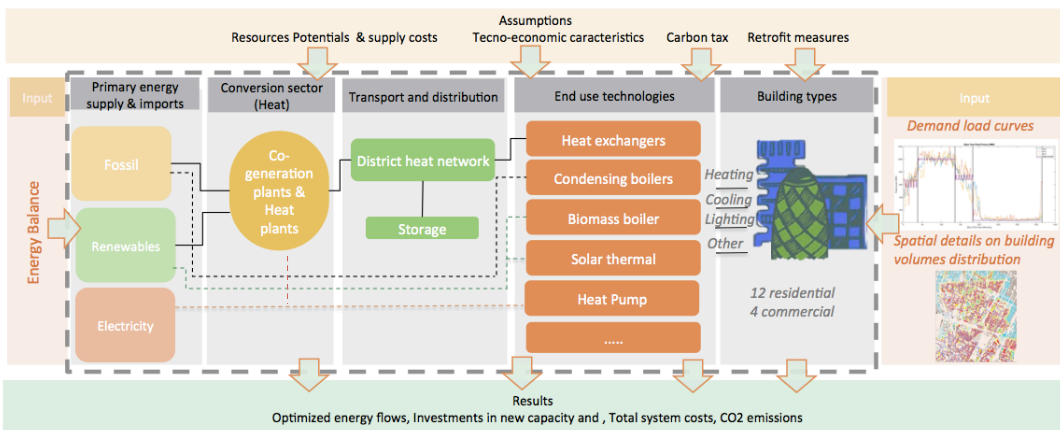


Figure 6-2: Overview of the RES. Commercial buildings include all non-residential buildings.

As better explained in Chapter 4 and Chapter 5, the energy balance of the city refers to 2005, whereas the buildings sector consumed 11.14 TWh, of which 2.68 TWh of electricity and 8.46 TWh thermal consumption from fossil fuels, correspondent to roughly 60% of total urban consumption. From 1990 to 2005, the population diminished from about 980,000 to roughly 900,800 inhabitants and emissions decreased by 18.7% from 6.27 to 5.1 Mt_{CO2}. The plan for 2020 is to further decrease the emission of 1.36 Mt_{CO2} in 2020 reaching more than 40% reduction from 1991 to 2020 (Città di Torino, 2012). Considering the purpose of the analysis, the demand sectors of the proposed model are limited to the Residential and Non-Residential sectors. From 2005 (energy balance) to 2015 (Base year) some analysis on new-building volume, the share of district heated volume and energy consumptions were developed taking into account the available statistical data and existing building standard as explained in (Mutani et al., 2016). Some small industrial activities were included in the analysis as well in terms of electric consumption and thermal consumption from district heating. Taking into account the reference 2617 normative HDD, the total building consumption in 2015 was therefore set equal to: 9.19 TWh/y of space heating consumption (62% residential and 38% non-residential as in Chapter 5) and 4.1 TWh/y (including small industrial activities) of electric consumption.

In the RES, the considered flows include both energy carriers and emissions. The supply part of the RES considers both local resources and import of commodities. Bearing in mind the urban boundaries, the model described in this Chapter mostly relies on the import of resources while the local production is mostly referred to renewables solar sources, municipal solid waste (MSW) and electricity production from CHP units. The most relevant details of the described technologies and commodities are described in the further subsections.

6.3.2 Demand Sector

The demand of the model is exogenous (user defined) and it is intended as the building volume to which 5 end-use services need to be provided: space heating (SH), water heating (WH), space cooling (SC), lighting (LI) and other electric use (OTHE). The choice to have the demand represented in terms of volume was driven by the need of introducing retrofit measures. In 2015, the heated volume of buildings was equal to 139 Mm^3 of residential buildings and 32.23 Mm^3 of non-residential buildings. In this chapter, the previously defined (Chapter 4) 36 residential Reference Buildings were further clustered into 12 RBs: 3 construction periods (pre 1980, from 1980 to 2005, after 2006) and 4 building types (apartment block AB, multi-family MF, terraced attached house TH and single-family detached house SF). This classification allows dividing the buildings constructed before the first energy regulation (before 1980) from the new ones (after 2006) and the ones built in the between. It was decided to reduce the number of building classes in order to have a controllable and manageable model. As already described, more than 75% of residential volume belongs to the AB category and more than 80% was built before 1980, leading this RB type to be most representative of the building stock. Non-residential buildings were classified for destination use volume into: schools SCH (16.4%), office buildings OB (11.6%), small commercial buildings CB (0.6%) and others OT (71.4%). As shown in Figure 6-3, building turn over was assumed constant, maintaining constant the evolution of building volume, meaning the all the demolished residential buildings are substituted by new buildings of the same type. The evolution trends of building turn over may be further investigated in future analyses.

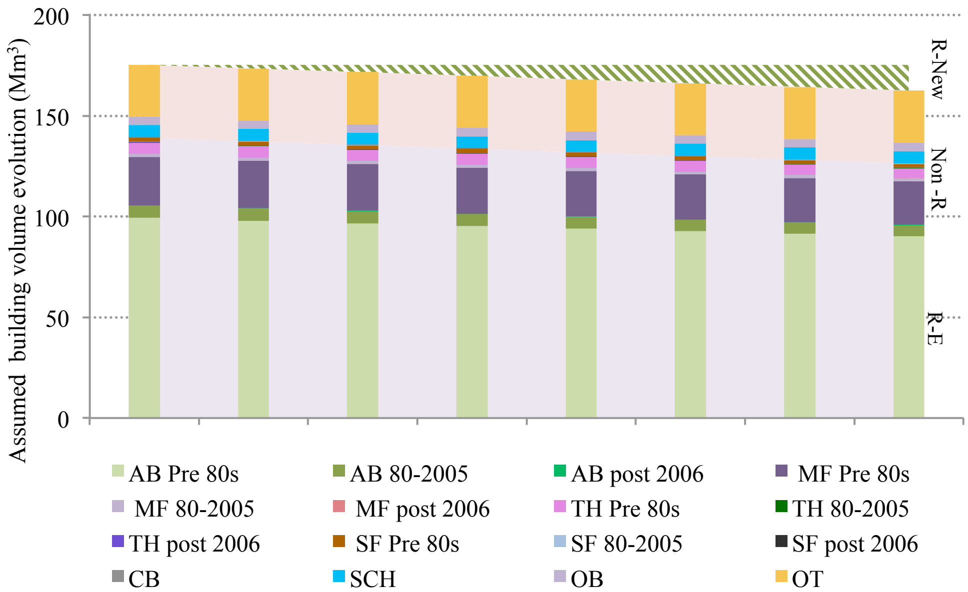


Figure 6-3: Assumed evolution of buildings volumes. R-New=residential new; Non-R= non-residential; R-E=Residential Existing.

The time resolution of the model was defined by analysing the real load thermal profiles of the urban district heating system and the yearly consumption of a set of 300 representative sample buildings, the same described in Chapter 5 (Delmastro et al., 2016a). The goal is to define representative "timeslices" (Tsl) in order to aggregate temporal periods characterized by a similar load. The timeslices selection is extremely relevant for the model outcome; its definition depends on the purpose of the analysis taking into account the always existing compromise among computational time and technical resolution. In the Torino-TIMES model, the definition of timeslices is defined according to the thermal load being aware that an underestimation/overestimation of renewable generation level may be encountered (Poncelet et al., 2016).

Figure 6-4 summarises the procedure (limited to residential buildings and space heating in this example) that shows: (i) the process of timeslice definition and (ii) the process for evaluating how to assess and disaggregate the energy service demand of the RBs into the identified timeslices.

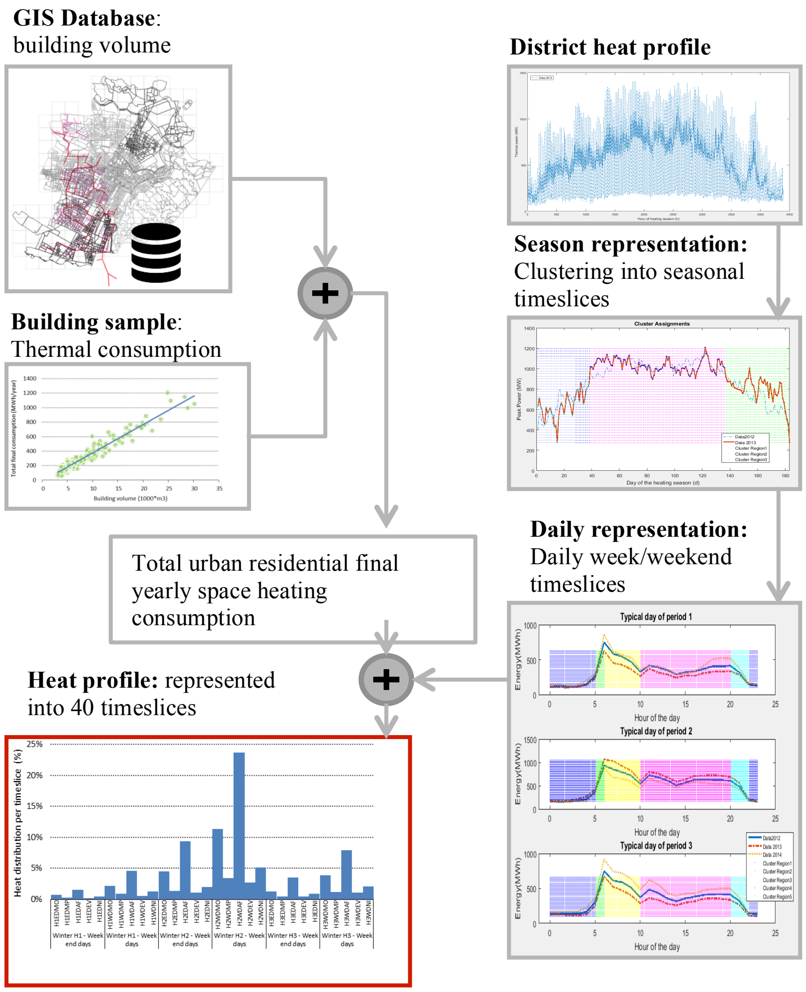


Figure 6-4: Considered temporal representation (example for space heating in the residential sector).

A seasonal disaggregation was derived by normalizing the available load profiles to the normative HDD and by clustering the similar peak powers with the k-means algorithm. The heating season in Torino lasts from 15th October to 15th April. Three "winter seasons" were clustered: H1 lasting 38 days from the beginning of the heating season, H2 lasting 98 days (high season) and H3 lasting for the remaining 47 days of the heating season. The remaining 182 days in which the heating system is off were clustered into NH "not-heating season". Two representative days (Week-Days WD and Week-End days WE) were identified for each of the four "seasons" and 5 diurnal time slices were identified on the basis of WD trends. Therefore, a total of 40 timeslices characterize the model. On the other hand, by knowing the RBs thermal profiles and the volume distribution of buildings it is possible to estimate the total urban thermal load profile (Mutani et al., 2016). The first step consists in scaling up the RBs thermal profiles with the total real thermal load and then disaggregating the load of each RB in the 40 timeslices while the time horizon goes from 2015 to 2050 divided into 9 time-periods (Figure 6-5).

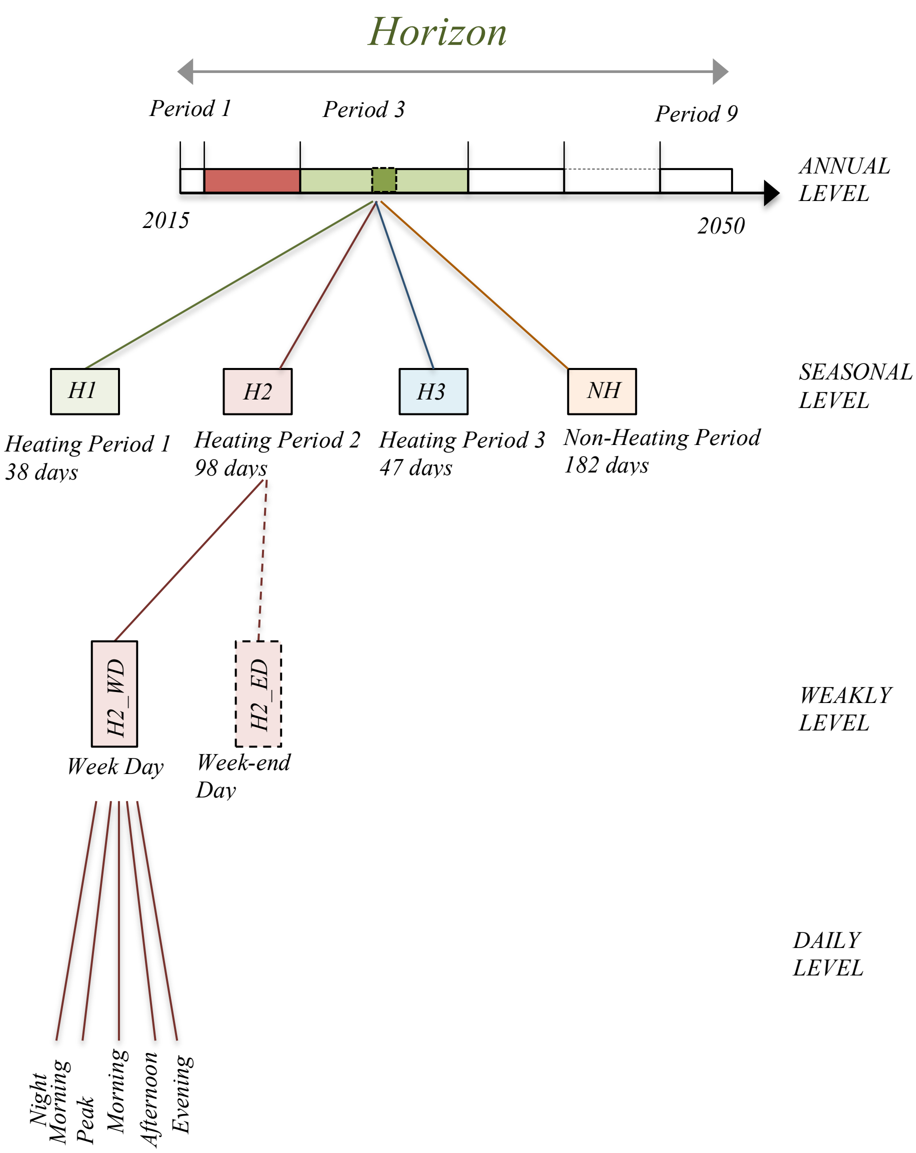


Figure 6-5: Timeslice levels.

A similar procedure of energy profiles disaggregation was performed for every energy service and every RB. Load profiles are developed for each end-use energy service. Most of the profiles derived from real energy data: residential water heating profiles were assumed equal to the ones of the DH non-heating period (excluding residuals from space heating season, Figure 6-6a); the thermal profile of schools derived from the work of Delmastro et al., 2016b (Figure 6-6b) as well as the electric profiles of schools (Figure 6-6c) and office buildings (Figure 6-6d). Residential electric load profiles refer to (*MICENE*, 2004). Heat demand intensities for space heating and cooling and water heating of new residential buildings are assumed to comply the nZEB target and, in this study, the indications (Ascione et al., 2016) are assumed.

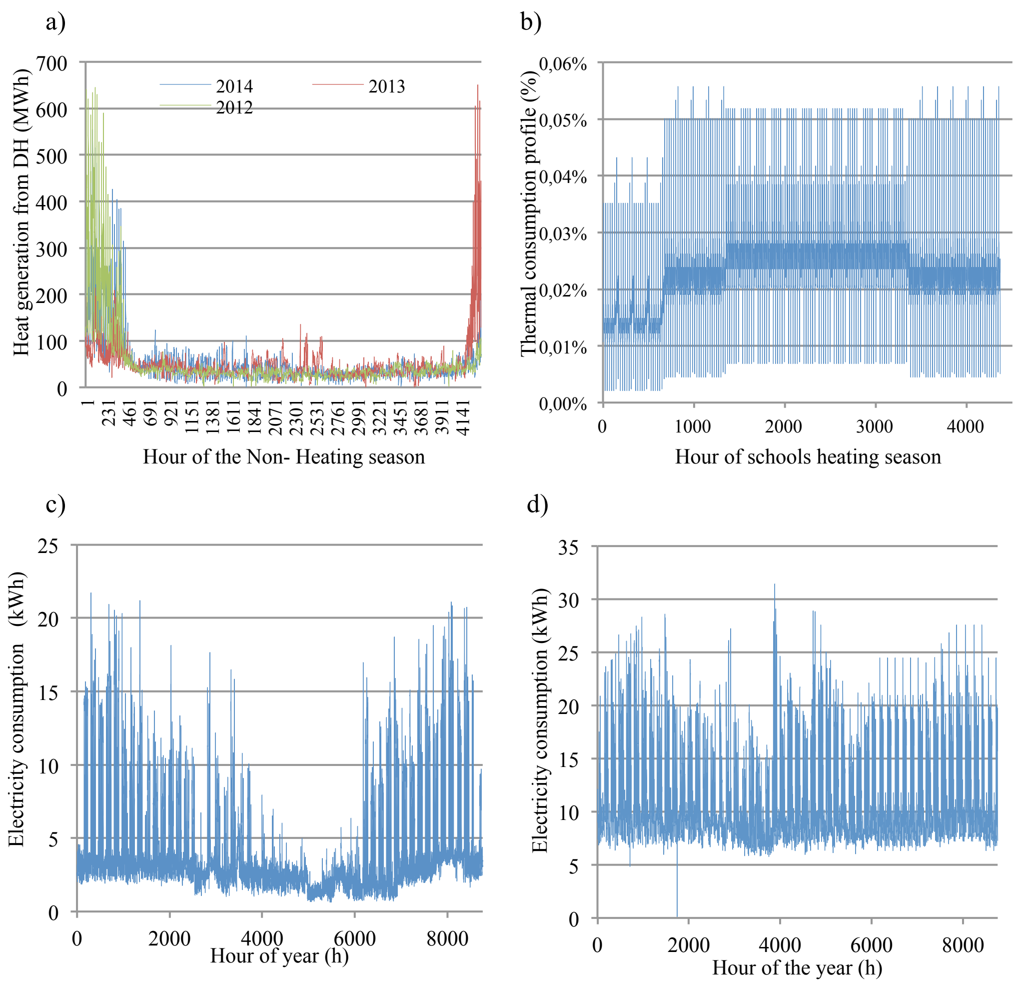


Figure 6-6: Real energy profiles for a) district heat during the non-heating season; b)thermal energy profile of a school; c) electricity consumption of a school and d) electricity consumption of an office building (Delmastro et al., 2016b).

6.3.3 Primary energy supply and imports

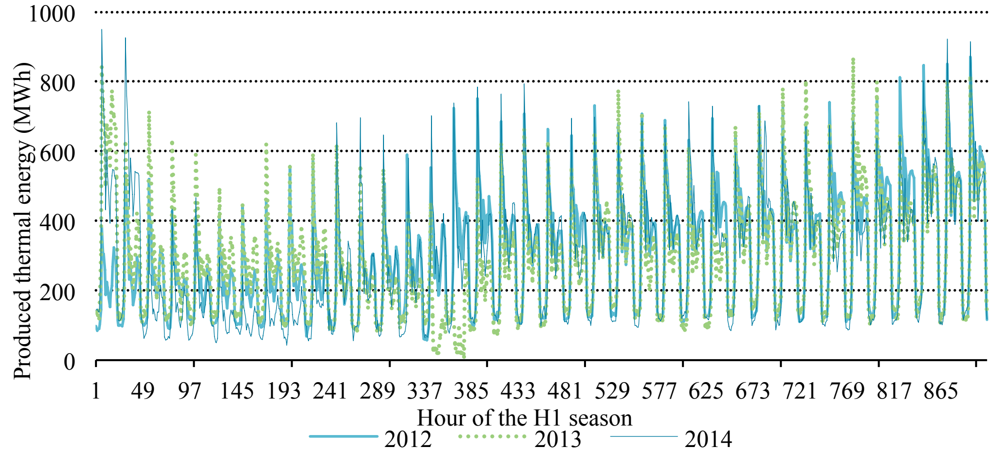
As it can be expected in an urban area, in the supply sector most of the resources are “imported” from outside the urban boundaries. MSW and solar energy technologies (hydro and geothermal not considered in this study) represent the only exceptions, considered as local resources. A total of four commodities (natural gas, biomass, diesel oil, electricity) are instead imported. Again, the main data source for fossil fuel consumption is the Turin Action Plan for Energy (Città di Torino, 2012) referred to 2005 data. In order to update these data, calibration with current district heating production (Gruppo *IREN,* 2015), new buildings energy consumption (Mutani et al., 2016) and statistics on average solar penetration in Italian urban areas (International Energy Agency, 2016) was necessary.

The modelled solar energy technologies consist both in rooftop and land PV and thermal panels. The available rooftop surface in the city of Torino was previously defined, with the support of GIS tools, in the works of (Bergamasco and Asinari, 2011). Considering the limited availability of rooftop surface, a constraint was set in order to ensure that the sum of solar thermal and PV new installations do not exceed the maximum available space. For land panels, a constraint on the maximum land surface was set. While the solar irradiation profile was derived by considering the monthly and daily average irradiance provided by the Joint Research Centre (JRC) database ("Joint Research Centre, European Commission, Photovoltaic Geographical Information System," 2018).

6.3.4 Conversion sector: large-scale heat generation technologies

Large-scale heat generation technologies include power plants and CHP for producing heat to be delivered by the local DH network. In 2014, approximately 27% of the total urban volume (57 Mm^3, or roughly 14 million m^2) was supplied by an entirely gas-based DH system completely produced, managed and distributed by the local utility company. In this Chapter, the specific production mix of the city of Torino, derived from (Gruppo IREN, 2015) is considered for the base year. The heat generation mix is composed by three gas based CHP units, described individually, with an installed thermal capacity of 740 MW, 1000 MW natural gas boilers and 12,500 Mm^3 of daily storage distributed in the city. The average yearly production in 2014 was roughly 2000 GWh_{th} (90% from CHP) and 950 GWh_{el}. More than 90% of the heat is supplied to the residential sector for heating and in some few buildings for water heating also. Figure 6-7a shows the heat produced from CHP in three consecutive years while Figure 6-7b shows the average normalized produced heat ordered in the Tsl and the resulting modelled profile. A set of new technologies to produce district heat was selected considering the previous analysis in Chapter 5 and (Delmastro et al., 2017a). It includes gas-fueled CHP, MSW based CHP, heat pumps, solar thermal heat plant fields with borehole seasonal storage and heat pump, auxiliary gas boilers (Table 6-1).

a)



b)

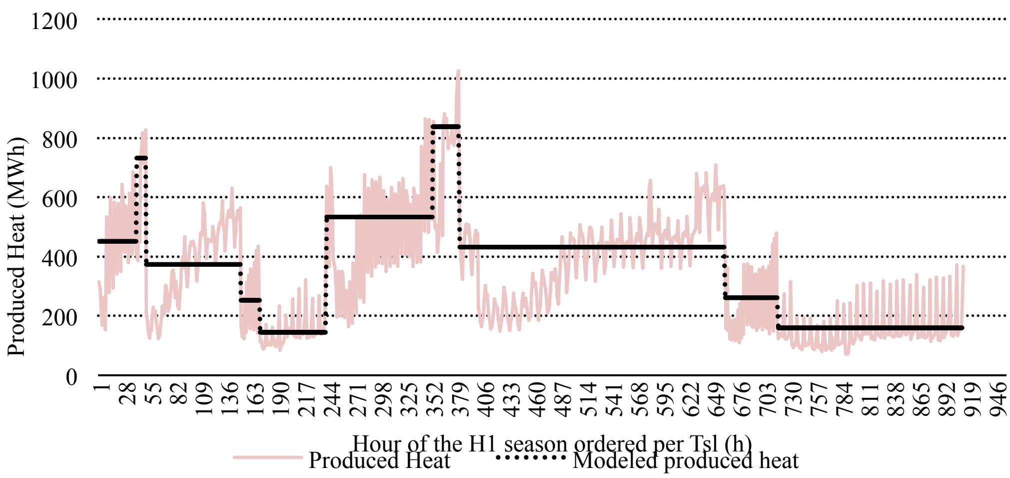


Figure 6-7: Real and modelled produced heat from DH. a) Real produced thermal energy energy in 2012, 2013 and 2013 and b) real average heat production from DH in the Tsl normalized at 2617 HDD and modelled heat production.

Table 6-1. Main technology aggregated data on large scale heat generation existing and future options *CHPR is intended as the ratio between thermal and electric powers; C mode is intended as condensing mode; UF= utilization factor; ** CEH is intended as the ratio between the difference of the difference of electric efficiency in condensing mode and electric efficiency in back pressure mode and the thermal efficiency. All new technologies are available from 2020.

	Tech	Capacity (MW)	Efficiency (%)	UF	Life	Inv cost (€/kW)	O&M fix (€/kW)	O&M var (€/kWh)	CHPR*	CEH**	Source
Existing	**Gas fired CHP**	Electric capacity in C mode: 1165	0.56-0.58 (electric in C mode)	0.63-0.3	10 - 25	-	32.73	0.0024	0.8-0.64	0.19 - 0.23	(Delmastro et al., 2017a; Gruppo *IREN,* 2015; Porchia et al., 2008)
	Gas fired HOB	Heat capacity: 1025	0.92-0.95	0.01 - 0.1	30 - 40	-	35	0.005	-	-	
New	**MSW fired CHP**	-	0.385 (electric in C mode)	0.75 - 0.3	30	1624	39.27	0.05	0.53 - 0.2	0.32	(Trattamento rifiuti metropolitani, 2016; Delmastro et al., 2017; Porchia et al., 2008)
	Gas fired CHP	-	0.56 (electric in C mode)	0.75 - 0.4	30	850.2	32.73	0.002	0.7 - 0.2	0.19	(Delmastro et al., 2017a; Dodds, 2014; Gruppo *IREN,* 2015; Porchia et al., 2008)
	Gas fired HOB	-	0.95	0.05	20	100	35.00	0.01	-	-	
	Large scale heat pump	-	2.86	0.6	20	1667	15.69	0.07	-	-	(Delmastro et al., 2017a; Lund et al., 2016)
	Large scale solar thermal	-	1	0.21	25	400 €/m^2	-	0.025	-	-	(Buonomano et al., 2018a; Delmastro et al., 2017a; Tonhammar, 2014)
	Large scale PV panels		1	0.13	25	150 €/m^2	-	0.025	-	-	(Candelise et al., 2013; "Joint Research Centre, 2017.)

6.3.5 Transport and distribution options: heat networks and storage

The district heating system in Torino is roughly 500 km long and in 2016 connected around 60 Mm^3 of building heated volume. The network is rapidly expanding with roughly 1 Mm^3/year of new connections and in the model 57 Mm^3 of connected users in the base year were considered (Delmastro et al., 2017a). The current district heat pipe network is sized to connect around 19.5 Mm^3 more volume (the already connected volume from 2014 to 2017 plus 20% of remaining connectable users) without new intervention in pipelines (Guelpa et al., 2017). In the city some areas (65.4 Mm^3 (Guelpa et al., 2017)) cannot be taken into account for expanding the district heating system for physical/territorial limits (i.e. the presence of hills and rivers), technical limits (buildings individually heated or characterized by small volumes) and heritage/historical constraints (city centre). This value (taking into account current thermal demand distribution) represents the upper limit for district heating expansion while the capital cost of pipeline networks considers an increment of transmission costs when the current connectable volume will be exceeded. The district heating system also includes 12.500 m^3 of daily storage tanks. As new options both daily and seasonal storage options are available. Losses were assumed equal to 11%. In Table 6-2, the main input data related to the considered technologies are summarized. The network investment cost was evaluated following the procedure proposed by (Frederiksen and Werner, 2014) and considering the current average heat density. This represents one of the limitations of the model as further explained in Section 6.5. The transport and distribution options are limited to DH, in fact, either low-pressure hydrogen networks or options for greening the existing gas network are not be included in the model and will be considered in further applications.

Table 6-2. Main aggregated data for transport and distribution options. UF= utilization factor

	Technology	Heat capacity (MW)	Efficiency (%)	UF	Life	Inv cost (€/kW)	O&M fix (€/kW)	O&M var (€/kWh)	Sources
Existing	Existing Network	1.77	0.89	0.4	25	-	8	0.0036	(Fakhri et al., 2017; Gruppo IREN, 2015)
	Existing daily storage	12,500 m^3	0.9	-	20	-	-	-	(Delmastro et al., 2017a; Gruppo *IREN,* 2015)
New	Network pipeline expansion	-	0.89	0.4	50	911.2	6.4	0.0029	(Frederiksen and Werner, 2014)
	New daily storage	-	0.9	-	30	135 €/m^3	4.1 €/m^3	-	(“Thermal Energy Storage,” 2013)
	New seasonal storage	-	0.6	-	30	60 €/m3	4.1 €/m^3	-	

6.3.6 End-use technologies and energy conservation measures

Among the buildings that are not connected to the DH network, in 2015 more than 80% of space heating demand is covered by natural gas while roughly 11% by fuel oil, 3% by electricity and only a small portion by biomass (Delmastro et al., 2017a). For the solar and biomass share, no specific data for Torino were found, therefore the urban share estimated for Italy by (International Energy Agency, 2016) was assumed in the model; while, the share among condensing and non-condensing gas boilers refers to (CRESME, 2017). Obviously, no investments can be made in existing technologies. As new technologies, alternatives to gas were taken into account such as air-source heat pumps and solar water heaters. The choice of micro-CHP (MCHP) types depending on the RB type was performed considering the work of (Dorer and Weber, 2009). Therefore, depending on the type of building, a total of three types of MCHPs were considered: Solid Oxide Fuel Cell (SOFC), Stirling Engine (SE) and Internal Combustion Engine (ICE). As heat pumps, integrated heat pump systems were taken into account: they provide space heating, cooling and water heating. Non-condensing boilers were not included as future options while biomass boilers were included as possible options for single-family buildings only (even if for air quality concerns they may be excluded by future regulations) (Table 6-3). For each building type, a different set of heat and cooling technologies was considered for a total of 110 heat technologies and 10 cooling technologies. 4 lighting technologies were included: incandescent lamps, halogen lamps, compact fluorescent lamps and LED. In future options, incandescent lamps will not be available.

Energy conservation measures (building retrofit) are directly represented in the model as in Figure 6-8. The measures directly contribute reducing the demand for residential space heating. The measures were selected as in Chapter 5 by means of a cost-optimal approach. Three different retrofit measures (Standard, Cost-optimal and Advanced) were proposed for all the RBs built before 2006, for a total of 24 interventions. In general, the Baseline measure involves window substitution, the Standard retrofit involves new envelope insulation and the Advanced measure involves new insulation coupled with other measures such as thermostatic valves and insulation of the distribution system (as in Chapter 5).

Table 6-3. Main aggregated data for end-use technologies. All the values referred to MCHP technologies refers to future estimated values (2025 for ICE and SE and 2030 for SOFC fuel cells), because with current values these technologies would have never been selected by the model as it will be further explained in Section 6.4.

	Tech	Heat capacity (MW)	Eff (%)	UF	Life	Inv cost (€/kW)	O&M fix (€/kW)	O&M var (€/kWh)	CH PR* (fix)	CEH **	Sources
Residential existing	Gas boiler	1749	0.81/ 0.93	0.2	25	-	4.6	0.007	-	-	(Danish Energy Agency, 2016; Delmastro et al., 2016a; IRENA and IEA-ETSAP, 2013; Paper, 2011)
	Heat exchanger	958	0.9	0.2	25	-	4.0	0.007	-	-	
	Oil derivate boiler	297	0.75	0.2	20	-	10.5	0.009	-	-	
	Electric boilers	122	1	0.05	15	-	1.9	0.009	-	-	
	Solar water heating systems	42	1	0.2	20	-	4	0.0052	-	-	
	Biomass boilers	25	0.65	0.2	15	-	24	0.009	-	-	
Non- residential (Non-R) existing	Gas boiler	1531	0.8	0.21	20	-	4.6	0.007	-	-	
	Heat exchanger	374	0.9	0.22	20	-	4	0.007	-	-	
	Oil derivate boiler	156	0.75	0.21	20	-	11	0.009	-	-	
New technologies	Gas boiler C/auxiliary A	-	0.96 - 0.88	0.2	25	128/93 (AB-MF) 175/ 124 (TH-SF) 64 (C only)	4.6	0.007	- -	- -	
	Heat pump	-	2.5/3 /3.4	0.3	15	277 (AB, MF and Non-R) 745 (TH-	13.8 37.3	0	-	-	

					SF)					
Heat exchanger (AB, MF and non-residential)	-	0.9	0.2	25	97	3.8	0.001	-	-	
Biomass boiler (SF only)	-	0.85	0.2	20	342.7	24	0.009	-	-	(Danish Energy Agency, 2016; Delmastro et al., 2016a; Paper, 2011)
Solar thermal rooftop	-	1	0.2 1	25	400 €/m^2	-	0.025	-	-	(Buonomano et al., 2018b; "Joint Research Centre, European Commission, Photovoltaic Geographical Information System," n.d.)
PV rooftop	-	1	0.1 3	25	150 €/m^2	-	0.025	-	-	(Candelise et al., 2013b; "Joint Research Centre, European Commission, Photovoltaic Geographical Information System," 2017)

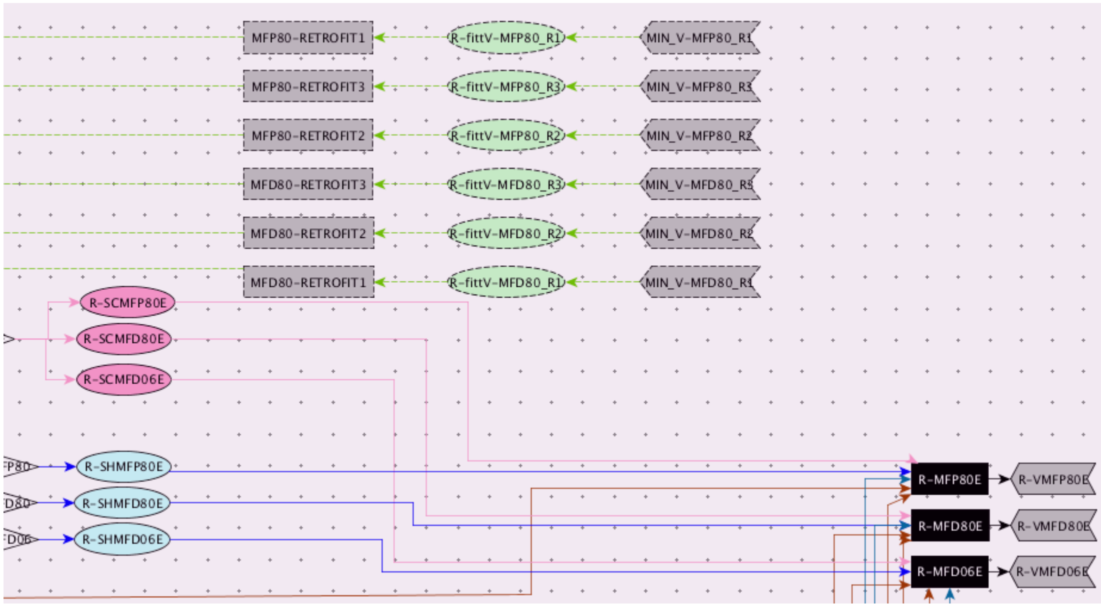


Figure 6-8: Representation of energy conservation measures for MF buildings in the RES.

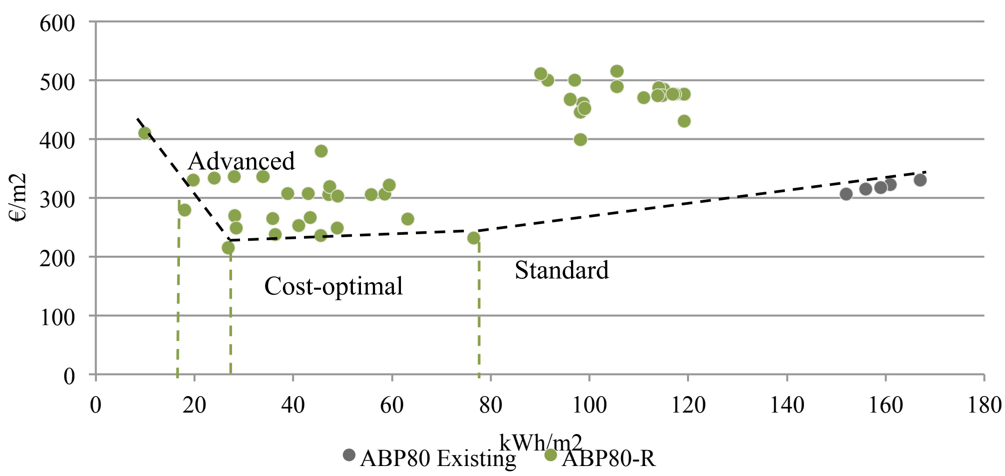
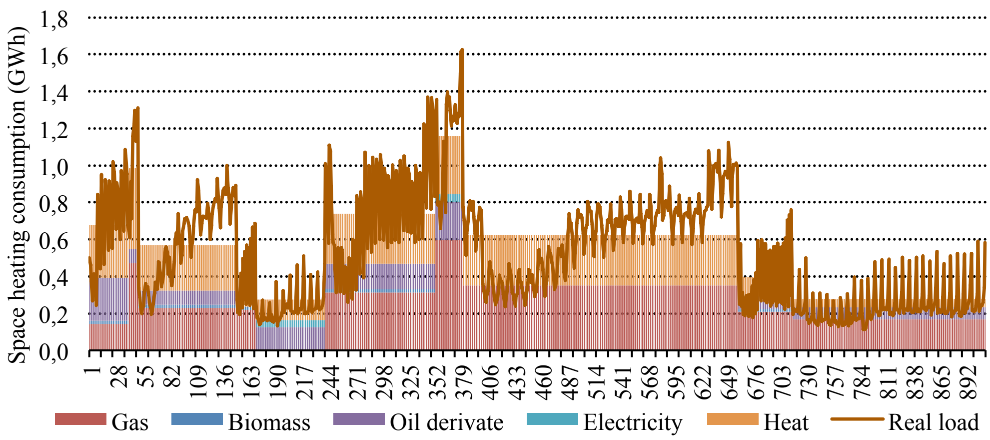


Figure 6-9: Selection of retrofit measures for Apartment Block built before the '80s.

As summarized in Figure 6-9, the measures are selected as proposed in (Delmastro et al., 2016a) considering a qualitative cost-optimal approach (Becchio et al., 2016) in which the global cost of the selected measure is not higher compared to one of the existing buildings. The investment costs of the measures were derived from (Regione Piemonte, 2016) and (Delmastro et al., 2016a). Considering presumed market constraints, cost-optimal and advanced measures were assumed available starting from respectively 2025 and 2030. By introducing the retrofit measures (that may be characterized by different space heating profiles), the operation of end-use technologies during the defined timeslices was modified (discontinuous operation), requiring additional constraints (Figure 6-10a and Figure 6-10b). This highlights the need of being extremely careful in controlling the model.

a)



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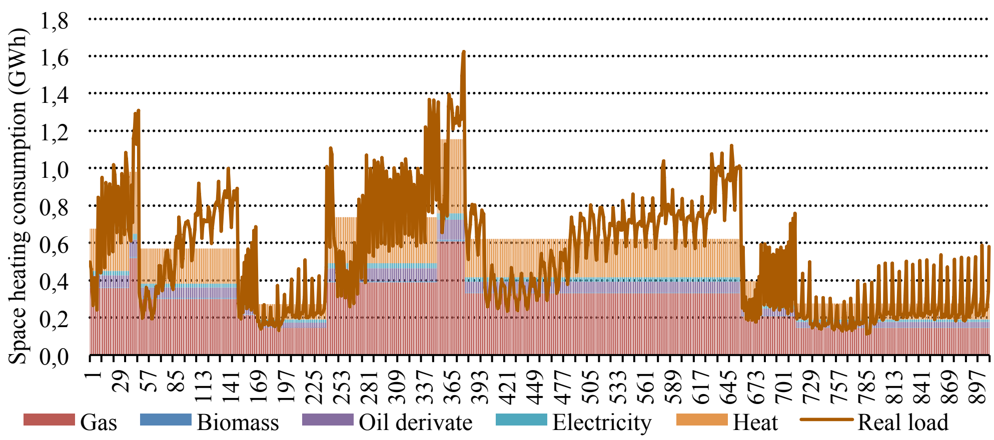

Figure 6-10: Space heating consumption of apartment block building: a) operation of end-use technologies per fuel type without constraints and b) correct operation of end-use technologies by fuel type.

6.3.7 Main assumptions, constraints and scenarios definition

In this application, the model was built for creating scenarios playing with seven main variables: discount rate, fuel and electricity prices, decarbonization level of the power sector, environmental and climate policies (i.e. carbon tax), minimum expansion of the district heating system and minimum renewables penetration. In particular, Table 6-4 summarizes the principal options taken into account for this application. High fossil fuel prices refer to the 6DS IEA-ETP 2016 scenario, while low fossil fuel prices refer to the 2DS IEA-ETP 2016 scenario values. Electricity and biomass prices evolution refer to the work of (Fakhri et al., 2017) while the heat production price is endogenously evaluated by the model. The adopted carbon tax refers to the 2DS IEA-ETP 2016 scenario and its trend is observable in Figure 6-11. The level of decarbonisation of the power sector refers to the 2DS/4DS/6DS IEA-ETP 2016 scenario respectively for High/Low carbon/Low. Figure 6-11 shows the evolution of emissions from grid electricity consumption with respect to 2015 levels for the three scenarios.

Table 6-4. Selected variables for performing the scenarios analysis.

Variable	Options	Source
Discount rate - DR	3.5%/5%/10%	User-defined, (García-Gusano et al., 2016)
Fuel and electricity prices - FP	High/Low	(Fakhri et al., 2017; IEA International Energy Agency, 2016)
Decarbonization level of the power sector - DL	Low/Low carbon/High (Figure 6-11)	(International Energy Agency, 2016)
Carbon tax- CT	Yes/No (Figure 6-11)	(International Energy Agency, 2016)
Environmental target - ET	40%/60%/80%	User-defined, reflecting EU targets
DH minimum expansion –DH_E	40-60% of space heating share/ >60% of space heating share/ No	User-defined
RES minimum penetration –RES_P	10% of solar/ 60% water heating from solar/No	User-defined

Table 6-5 presents the variables that were combined to generate the different scenarios), in particular, scenarios are environmental oriented (involving emission targets and carbon tax) and technology oriented (involving several DH penetration rates). Three scenarios, environmental oriented, are discussed at first:

- Baseline: in which the planned 40% emission CO_2 reduction target to 2030 (compared to 1990) is set without any further CO_2 constraints to 2050. In (Città di Torino, 2012), the declared emission target for 2020 (compared to 1990) is 40%, but it was not achievable by the model (probably for the climatic correction) therefore the target was applied to 2030;
- S1: in which a 60% CO_2 reduction target is set to 2050 (compared to 1990 levels);

- S2: in which a 80% CO_2 reduction target is set to 2050 (compared to 1990 levels);

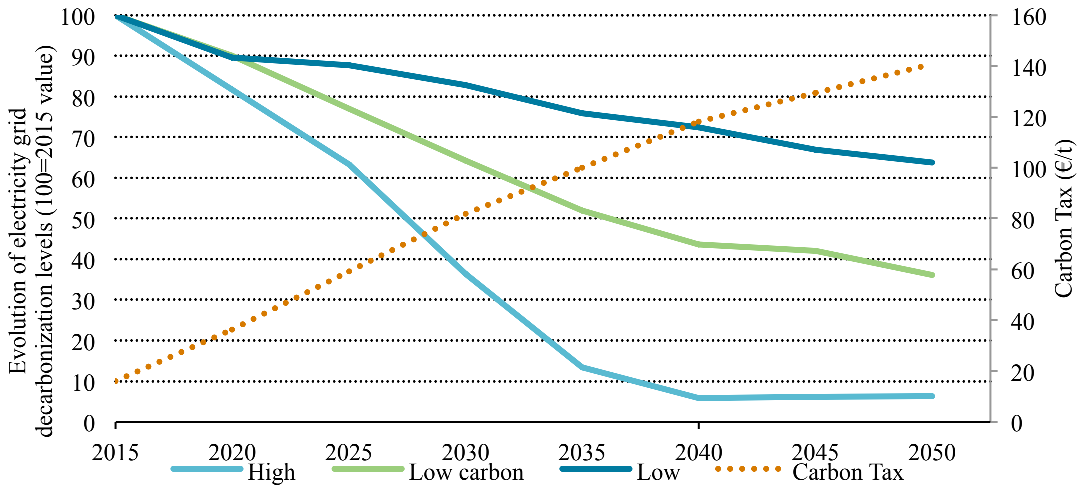

Figure 6-11: Evolution of some scenario variables.

The other scenarios were generated starting from S2 and by adding a carbon tax (S2-CT) and by adding a constraint on minimum district heating penetration (S2-DH). All the other variables were adopted for performing the sensitivity analysis. These scenarios were selected after running many simulations and by analysing them through a specific interface build up to ease the understanding and visualization of scenarios (Figure 6-12).

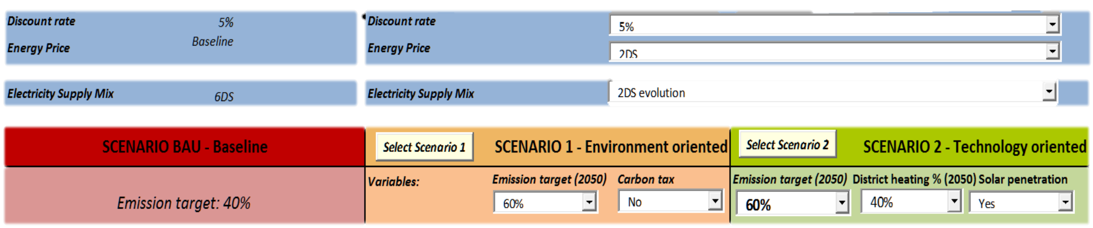

Figure 6-12: Interface master page for selecting and visualizing the scenario results.

Table 6-5. Generated scenarios.

Scenario Name	DR	FP	DL	CT	ET	DH_E	RES_P
Baseline	5%	High	Low	No	40% (2030)	No	60% solar WH for New buildings
S1	5%	Low	High	No	60% (2050)	No	60% solar WH for New buildings
S2	5%	Low	High	No	80% (2050)	No	60% solar WH for New buildings
S2-CT	5%	Low	High	Yes	80% (2050)	No	60% solar WH for New buildings
S2-DH	5%	Low	High	No	80% (2050)	40-60% min share of DH	60% solar WH for New buildings
Sensitivity Analysis	☑	☑	☑	☑	☑	☑	☑

The major constraints adopted in the model are summarized in Table 6-6 and are related to the uptake of new heat technologies, the total deployment of energy conservation measures, the land and rooftop available surface for solar technologies, the minimum utilization factor for CHP units and the maximum availability of MSW.

Table 6-6. Major constraints.

List of constraints	Type of limit
Yearly availability of RFD for DH production	Upper bound from (Trattamento rifiuti metropolitani, 2016)
“Export” of produced electricity	Upper bound (assumed equal to the base year value)
CHRP operational range of CHP	Upper and lower bound
Solar thermal hot water supply of new buildings	Lower bound equal to 60% of required demand
Available roof-top and land surface for solar technologies	Upper bound
Yearly capacity factor of CHP units	Lower bound (per timeslice in the base year, yearly in other time periods)
Capacity factor of DH heating only boilers	Upper bound
Heat pumps efficiencies	Dynamic evolution from (International Energy Agency, 2016)
Supply from existing DH plants	Lower bound up to 2025
Large scale heat pumps deployment constraint	Upper bound until 2030

New heat pumps technologies deployment constraint	Upper bound until 2030
Heat and electricity supply from existing technology	Dynamic lower bound until exhaustion
Conservation measures penetration rate	Dynamic lower and upper bound
Water heating/space heating production ratio of existing technologies	Dynamic lower bound

6.4 Results

This section presents the principal results of the scenario analysis by applying the presented TIMES model. The scope of this section is to show quantitative results from very aggregated to very disaggregated ones in order to make the reader understand the potentiality of the model application. At first, results are related to the three scenarios (Baseline, S1 and S2) involving upper bounds on CO_2 emissions, allowing the model to choose among the full technology portfolio.

6.4.1 Outlook

The three presented scenarios show decarbonization alternative paths that could reduce the urban carbon emissions by at least 40% to 2030 and respectively 60% and 80% in Scenario S1 and Scenario S2, compared to 1990. This paragraph analyses how the transition influence three main aspects: the urban consumption mix (intended as primary energy plus imported electricity), the carbon emission decomposition by sector and the total system cost required to support the transition.

As it can be observed from Table 6-7 and Figure 6-13, the Torino 2015 energy mix highly relied on natural gas with a lower share of oil products and renewables. All the scenarios highlight a progressive fuel switching from fossil fuels to lower carbon energy sources: phase-out of oil products, the decline of natural gas, increased use of renewables and electricity. The share of renewables would considerably increase, mostly related to solar PV for electricity generation, solar thermal panels for hot water production and MSW for CHP production (only in Baseline and Scenario S1). High efficient pellet stoves are also contributing to this renewable share, being selected for single family and terraced houses (this option may be reviewed in further applications taking into account air quality regulations in urban areas). Two major trends emerge: (i) the reduction of urban consumption is achieved by fuel switching, efficiency improvements and energy conservation as it will be seen in next paragraphs; (ii) an increased level of electrification. In particular, the higher electrification is observable in Scenario S2 (deep decarbonization) in which the decarbonization of power generation outside the city is very high.

Table 6-7. Urban consumption mix.

	Base Year 2015	Baseline 2050	Scenario S1 2050	Scenario S2 2050
Urban consumption mix (TWh)	15.91	13.14	10.7	8.48
Fossil Fuels (%)	99.9%	86.2%	79.8%	49.6%
Natural gas	94.6%	86.2%	79.8%	49.6%
Renewables (Solar + biomass)	0.1%	6.9%	8.4%	11.7%
Solar + biomass + MSW	/	13.8%	16.8%	11.7%
Net Imported Electricity	0%	0%	3.4%	38.7%

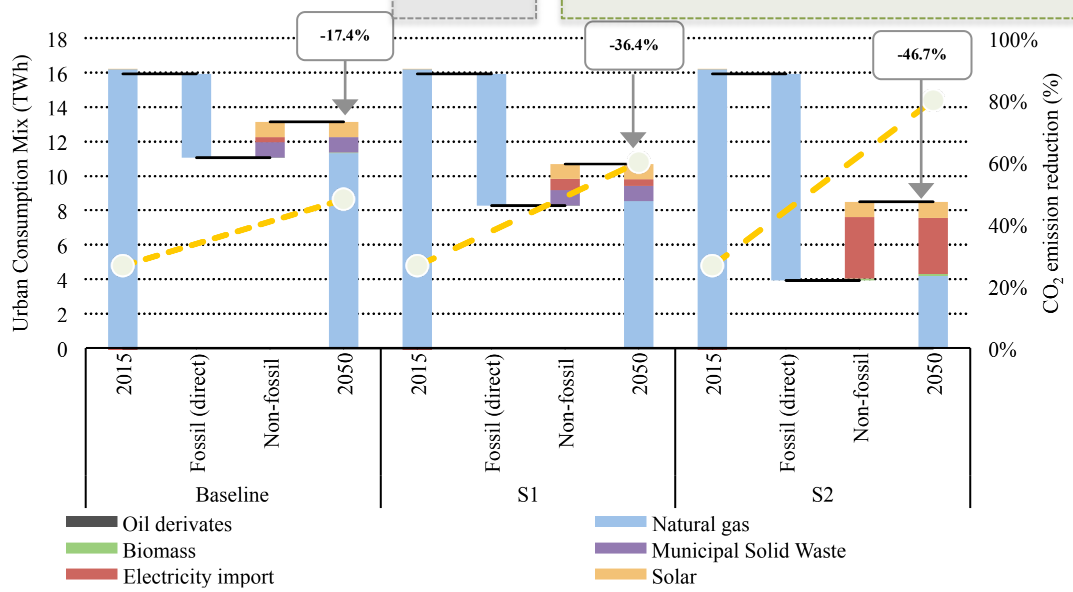

Figure 6-13: Total urban consumption (primary needs plus net imported electricity).

In 2015 carbon emissions accounted for 3580 kt_{CO2} showing a decrease of roughly 23% compared to 1990 and progressively decreasing in 2030 and 2050 to comply with the proposed environmental targets (Figure 6-14). Figure 6-15 shows the carbon emissions decomposition into the energy sectors. The largest share of 2015 carbon emissions was related to heat and power generation (51.6%), followed by the residential sector (24.5%), the non-residential sector (21.9%) while the remaining emissions came from the net import of electricity (2%). The evolution of CO_2 emissions clearly reflects the fuel mix shift and the penetration of new technologies. In all the scenarios, non-residential direct emissions would considerably be reduced, meaning a shift to electricity and/or district heating for heating purposes. In 2050-Baseline, no emissions from electricity imports are visible since, considering a net electricity balance, the cogeneration plants and PV system would produce all the annual electricity needs. Therefore, 95% of emissions are due to gas utilization and the remaining 5% to MSW combustion. Scenario S1 further reduces 2050 carbon emissions to 1852 kt_{CO2}, mostly related to heat and power generation (76.6%), but showing a 0.4% associated to net electricity import (the electricity produced in the urban area is not sufficient to cover yearly needs). In S2 emissions reduction to 2050 is targeted as 80% reduction compared to 1990 levels, accounting 926 kt_{CO2} of which the higher share (40.6%) is due to the residential sector while 8% from net electricity imports. This last information implies that the further reduction of thermal needs (due to energy conservation measures) impacts on the future technological choice (from district heating to individual highly efficient boilers or heat pumps). The increase of carbon emissions from net electricity imports is on one hand related to electrification of end-uses, but mostly to the reduction of district heating CHP capacity. The import of electricity is an option for both scenarios S2 and S1, considering a power sector almost decarbonized to 2050 (<40 gCO_2/kWh in 2050).

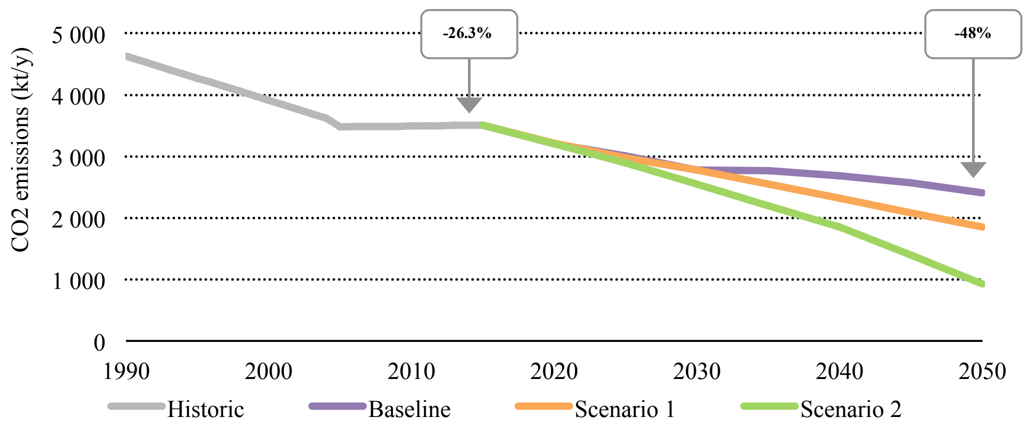

Figure 6-14: Evolution of urban emissions.

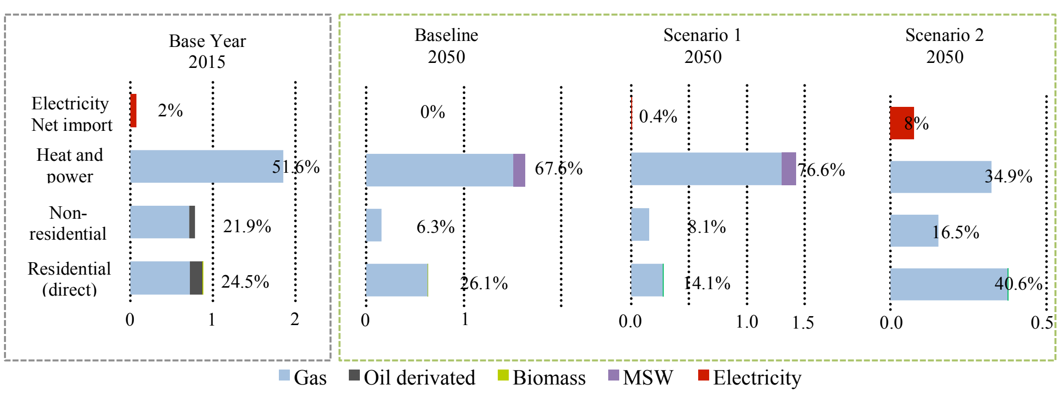

Figure 6-15: Urban emissions by sectors (Mt/y).

Figure 6-16 shows the costs, compared to Baseline, to reach the decarbonisation proposed in S1 and S2; a portfolio of demand reduction, higher efficiency technologies and a higher share of renewable is a prerequisite, requiring financial efforts. Interestingly, the total system cost (sum of investments, fix and variable O&M) does not consistently increase, and in S1 decrease, with respect to Baseline. The investment costs of S1 and S2 would not necessitate unreasonable supplementary financial efforts (+973 million € from S2 to Baseline), almost offset by a reduction of operation and maintenance costs. Significant costs would probably be required to support the decarbonization of power generation outside the city boundaries. Even if with lower decarbonization efforts, S1 is providing more savings in operational expenditures compared to S2 because it relies more of the existing district heat network infrastructure. Furthermore, part of the renewable quota of Scenario S2 is related to imported electricity (not produced inside the city) and, therefore, not contributing to the reduction of operational costs.

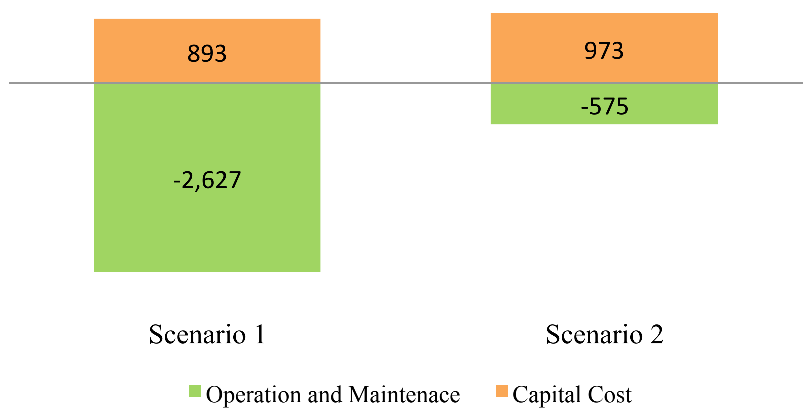

Figure 6-16: Total system cost (million €) compared to Baseline in the period 2015-2050 (discounted at 2015 value).

6.4.2 Building end-use energy services: energy demand and final energy consumption

This subsection provides an overview of how building final energy consumption would evolve from 2015 to 2050. The evolution of residential final energy consumption is related to four main factors that will be further analysed: stock turnover, fuel switching, energy efficiency improvements and building retrofit.

Stock turnover (Figure 6-3) is related to the building volumes to which energy service demands need to be supplied (demand of the model). In each Reference Building, the energy service requirements are assumed to be constant with exception of space heating where retrofit options are available. Therefore, stock turnover impacts on the total building final energy service needs (all new buildings assumed as NZEB). Due to stock turnover, the only energy service demand that is growing is space cooling with a growth of 15% from 2015 to 2050.

Fuel shift and efficiency improvements can be observed in Figure 6-17 and Table 6-8. The 2015 residential final energy mix was dominated by fossil fuels and heat, followed by electricity and renewables. Even if electricity would increase its share in covering end-uses demand, in 2050 natural gas remains a dominant commodity. Major differences among scenarios are related to the heat share driven by the thermal demand reduction (Figure 6-18). As also emerged in Chapter 5, a thermal demand reduction is translated by a lower need of capacity, but it will impact the district heating strategies. Actually, in the Baseline scenario, the 2050 heat share would diminish meaning that the network would not expand and the total district heating capacity is lower (technologies at the end-of-life are not replaced); considering the lower demand and the low environmental target of this scenario, investing in new district heating capacity wasn’t profitable. In 2050-Scenario S1, the heat share is instead growing: the reduction of heat demand move together with a district heating network expansion. This trend is not followed by Scenario S2 that would introduce more retrofit to further reduce the heating demand, but would not expand the district-heating network (with the proposed technologies it wasn’t possible to reach the target), therefore, replacing the capacity at the end of life with lower capacity and investing in individual highly efficient boilers or heat pumps. Another interesting information is the increase in solar production (covering water heating uses and producing electricity). On the one hand it contributes to the reduced electric consumption (but covering a higher share), together with energy efficiency improvement in lighting and appliances.

Table 6-8. Residential final consumption mix.

	Base Year 2015	Baseline 2050	Scenario1 2050	Scenario2 2050
Residential final consumption mix (TWh)	7.09	4.47	3.65	3.51
Fossil Fuels (%) (Natural gas only in 2050)	58.9%	65%	37%	52.6%
Heat	25.9%	16%	38%	18.7%
Renewables	1.2%	7.1%	9.1%	12.1%
Electricity	14%	11.9%	15.9%	16.6%

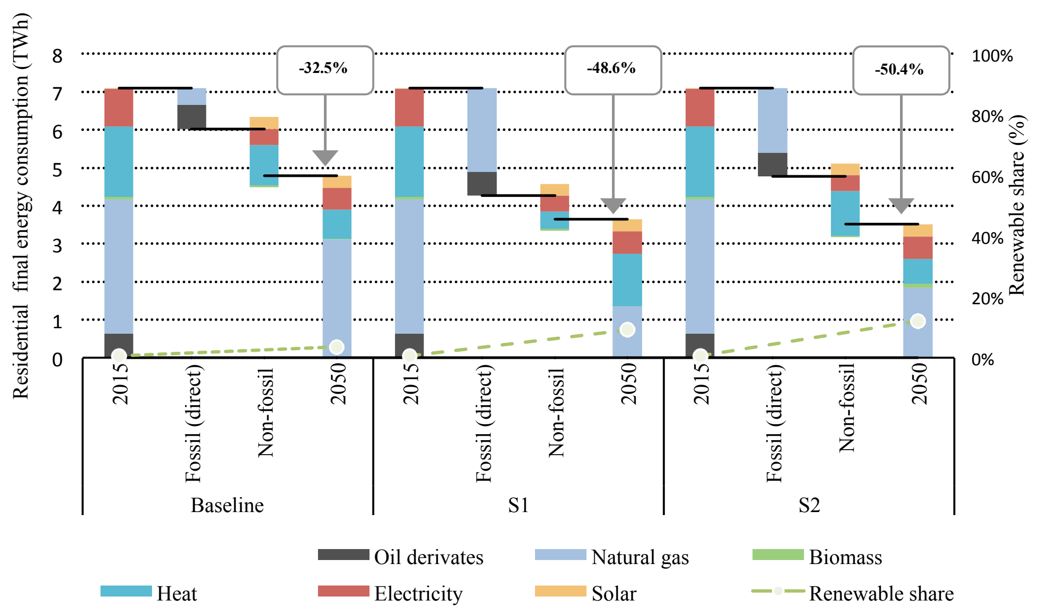

Figure 6-17: Final residential energy consumption by fuel.

With a higher level of details, Figure 6-18 presents the fuel mix for supplying thermal energy (space heating plus water heating) to the different building types. It reflects what previously explained showing that the residential 2050 final fuel mix significantly changes among the scenarios. A common trend in all scenarios is the complete replacement of oil-based boilers and the presence of natural gas as a dominant commodity. Reflecting what previously observed, together with the decrease of thermal energy demand, the lower cost solution in the Baseline scenario is represented by a high penetration of efficient gas boiler rather than a DH network expansion (district heating area limited to certain areas). To reduce carbon emission levels, Scenario S1 follows a different strategy having a higher share of district heating, a lower share of natural gas boilers, 0.2% share of electricity (heat pumps) and increasing renewables (solar plus high efficient pellet stoves for single family). This choice is also driven by the possibility of covering part of electricity demand thanks to the CHP units of the DH system. The S1 trend is not maintained in the decarbonisation scenarios S2 where the share of district heat is reduced to 23.3% but supplied with a cleaner mix (as will be seen in Figure 6-25) and the remaining part of the demand is covered through 0.3% electricity (heat pumps in this scenario), 62.4% natural gas boilers and 14% renewables. Clearly, final electricity consumed by heat pumps will result in higher useful energy (COP >2.5). The trends in fuel switching are distributed diversely among building types: obviously, all the district heat is supplied to compact buildings while high efficient pellet stoves penetrate into low compactness buildings. Heat pumps cover 1% and 1.6% of the thermal demand respectively in S1 and S2 (not included as an option for very old compact buildings with assumed radiators as heating terminals). In general, how it can be expected, a higher share of renewables is observable in buildings with low compactness. In all the scenarios, in new buildings solar energy covers at least 60% of water heating demand and heat pumps are installed to cover part of the space heating demand (3.5% in S1 and 8% in S2).

Residential electricity consumptions for end-use energy services (excluding non-residential electricity uses) would decrease from 2015 to 2050 in all the scenarios. Figure 6-19 shows the breakdown of residential electricity consumptions for 2015 and for 2050-Scenario S2. With regard to residential electricity consumption, all the scenarios behave similarly to S2. For all residential end-uses, devices with increased efficiency will progressively penetrate in the stock by for example substituting electric water heaters with solar thermal systems, and inefficient light bulbs with LED lamps. This would change the breakdown, allocating the higher electricity consumption share to electrical appliances (“Others”).

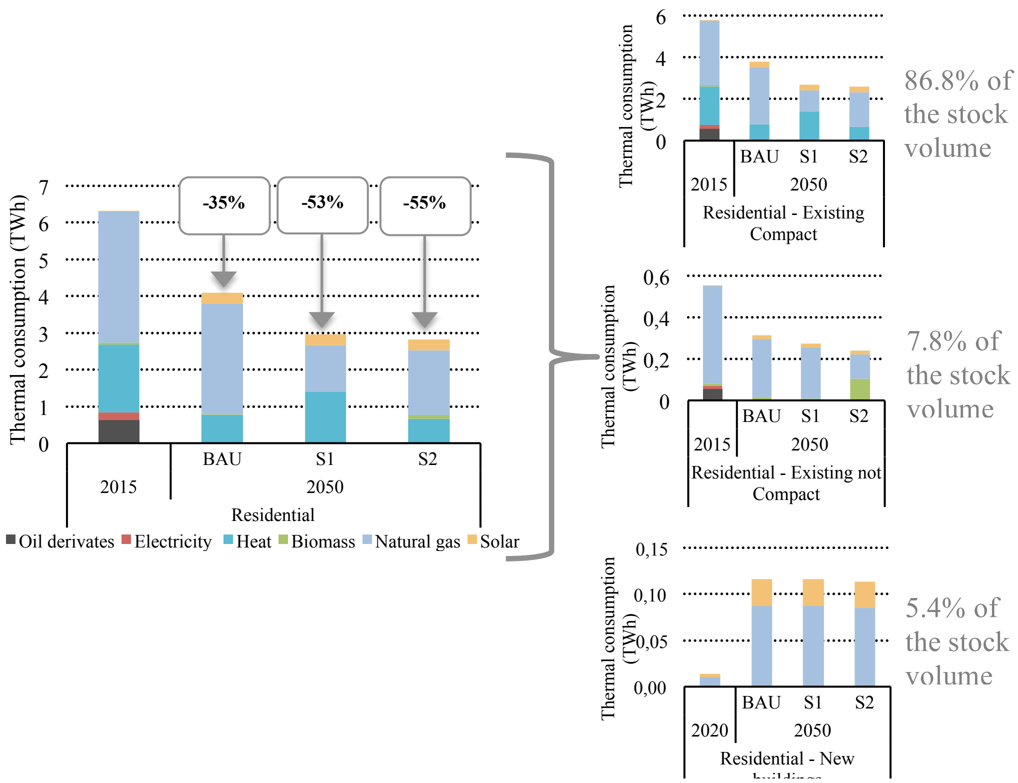

Figure 6-18: Thermal consumption of residential buildings per building types.

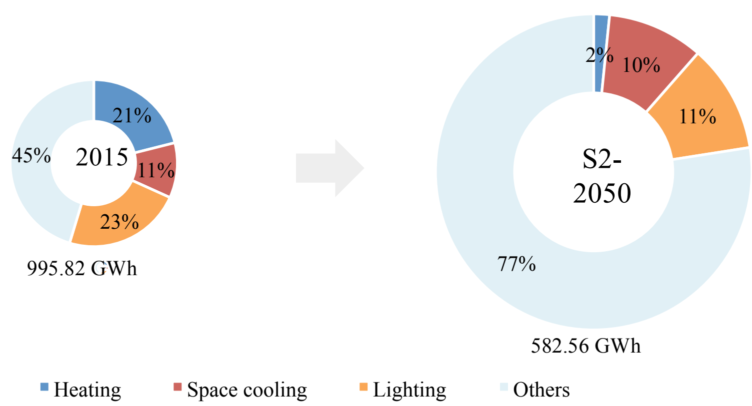

Figure 6-19: Electricity breakdown among energy services (excluding non-residential electricity for other uses rather than space heating).

The effects of fuel switching and efficiency improvement, stock replacement and energy conservation are shown in Figure 6-20 where the evolution of residential space heating consumption can be observed. Space heating consumption accounted for 6.3 TWh in 2015 and would progressively decrease in 2050 to 3.8 TWh in Baseline, 2.66 TWh in S1 and 2.53 TWh in S2. The share among these three parameters differs among the scenarios even if the retrofit option is always the more significant, while fuel switching and efficiency improvement and stock replacement equally contribute reducing the consumption. It can be observed that, for a higher decarbonisation, greater importance is devoted to building retrofit, contributing more than 80% to consumption reduction in both S1 and S2. In fact, the majority of energy savings from building retrofit are visible from Baseline to S1 while from S1 to S2, just a 5% reduction is noticeable. In general, the energy performances of buildings are continuously improving thanks to building retrofit and the average thermal energy intensity decrease from 42.2 kWh/m^3 in 2015 to 25.1 kWh/m^3 in Baseline, 17.53 kWh/m^3 in S1 and 16.7 kWh/m^3 in S2 in 2050.

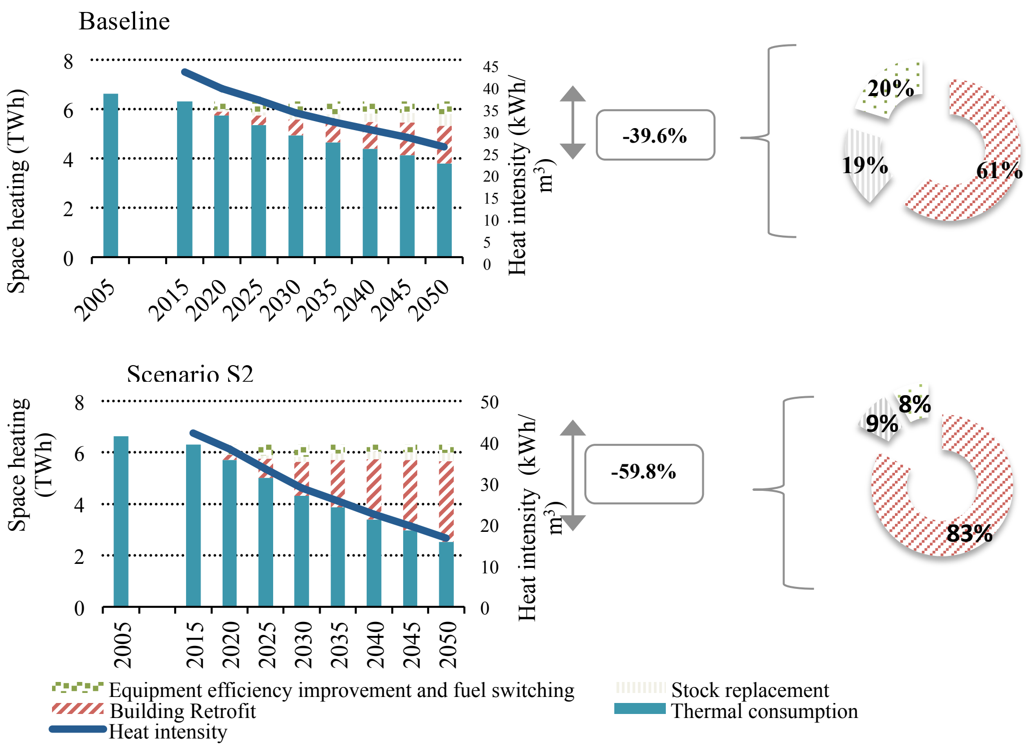

Figure 6-20: Residential space heating energy consumption evolution in Baseline and S2.

Considering the high importance of building retrofit, a specific focus on the spread of retrofit measures into Apartment Block buildings is provided in Figure 6-21. Both the type of measures and the involved volumes per building types are different among scenarios. In Baseline, 48.18 Mm^3 are involved in building retrofit from 2015 to 2050 while in S1 and S2 respectively 91.42 and 95.9 Mm^3. In Baseline, 18.8% of retrofit measures are Standard, 78.8% are Cost-optimal and only 2.5% of measures are Advanced (only into post-’80 buildings). To further decarbonize, a higher share of Advanced measures (both in pre-80s and post-80s) is promoted in S1 and S2 scenarios always maintaining a great majority of measures as cost-optimal. In Scenario S2, the spread of advanced measures in anticipated with respect to the other scenarios, starting in 2030.

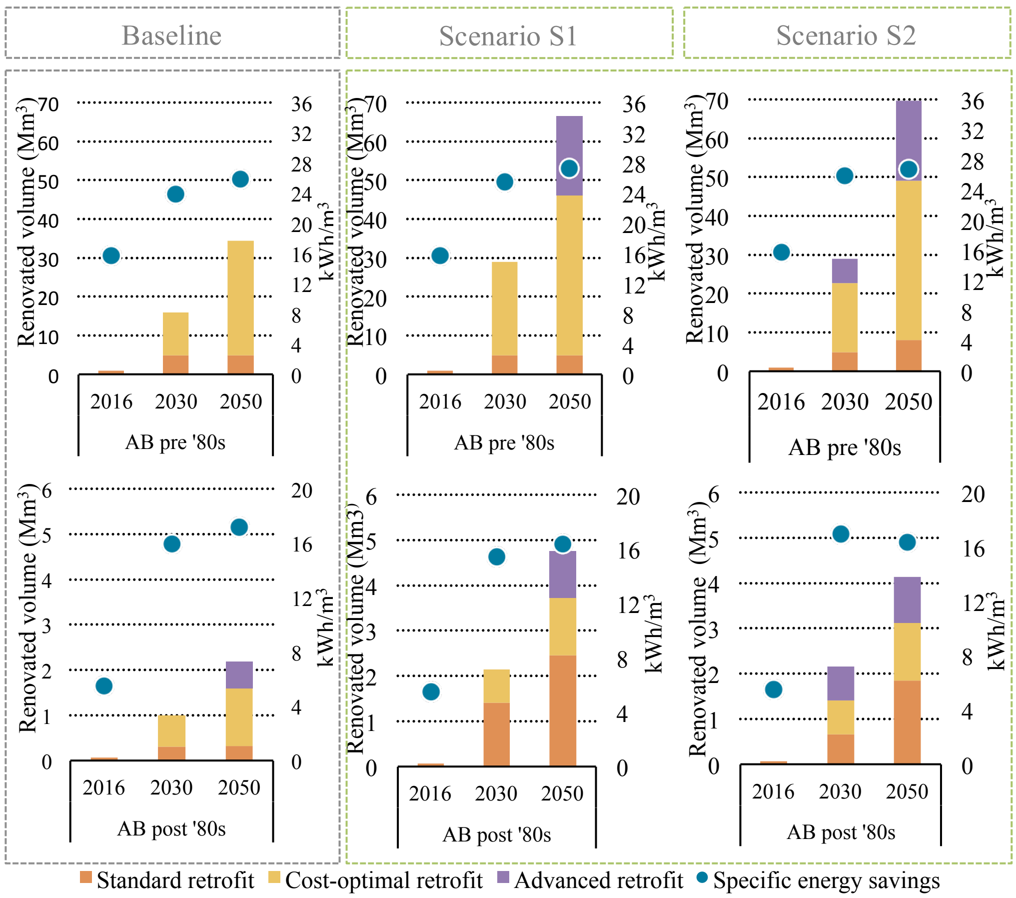

Figure 6-21: Retrofitted volumes and space heating energy intensities for the different residential AB buildings.

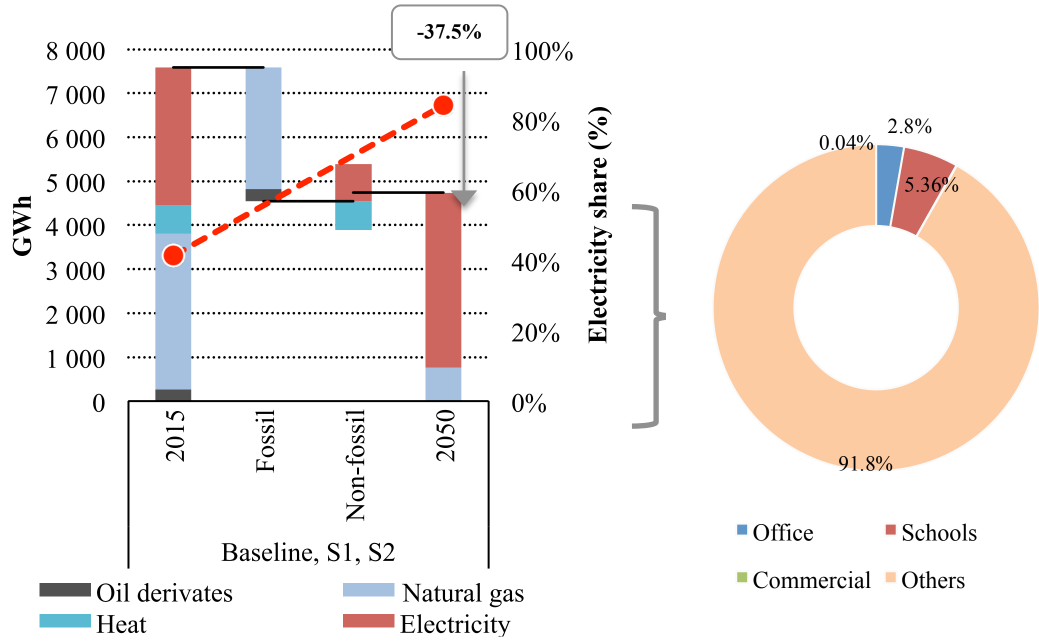

Figure 6-22: Final non-residential energy consumption by fuel.

For non-residential buildings, stock turnover and building retrofit do not have any impacts (wasn't the focus in this application) since the stock is not assuming as evolving and retrofit options weren't included in the model. Therefore the thermal and electric energy needs are constant in the time period 2015-2050, accounting respectively as 3.61 and 3.14 TWh. In this case, all the scenarios behave the same (Figure 6-22) selecting heat pumps and new gas boilers for covering the heat demand, completely removing oil boilers and heat exchangers. In 2015 thermal final energy consumptions equalled 4450 GWh covered by 85.3% fossil fuels (55.7% natural gas) and 14.7% by heat. In 2050, the same 2015 thermal demand is covered 53% by electricity (heat pumps) and 47% by natural gas boilers with a final consumption of 1605 GWh. Electricity consumptions for space heating would grow by roughly +27% from 2015 to 2050 in all the scenarios. This is mostly justified by the fact that the heat pump penetration is not constrained by the construction period of the building and temperature compatibility. Without this constraint, heat pumps would have probably been penetrating with higher shares in residential buildings as well, therefore, a deeper analysis on the costs associated to the conversion from traditional systems to heat pumps in old buildings would be necessary in future works.

6.4.3 Heat and electricity generation mix

Taking into account the adopted assumptions, electricity is the only commodity growing during the considered time horizon (roughly + 10.5% in all the three scenarios). In 2015, a high amount of electricity was produced by the existing CHP plants (as a net balance, all the electricity demand is covered by CHP with a net export of 2%).

Figure 6-23 shows that, in the 2050 Baseline scenario, net electricity production would be higher than the final demand and it is 88% produced by CHP units and 12% by newly installed PV.

This situation is not followed by S2, that considering heat savings and the assumed decarbonisation of the power sector, would import +244% of the self-produced electricity (58% by CHP and 42% by PV). S1 is in between Baseline and S1 resulting in a net electricity "importer" in 2050 (+9% of the self-produced electricity).

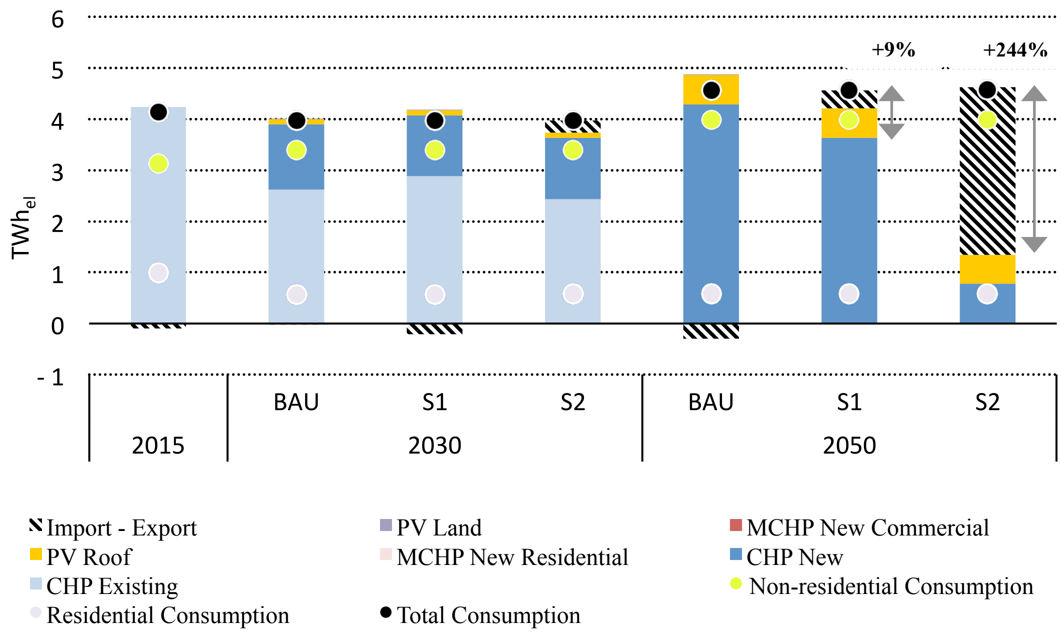

Figure 6-23: Electricity generation mix.

In addition to what previously affirmed, it is possible to sustain that the increased import of "electricity" is also driven by heat savings correspondent to a reduced capacity needs in the heat sector, reducing the capacity of installed CHP units. An overview of district heat production, heat and electricity generation and installed capacity is observable in Figure 6-25 and Table 6-9. The district heat production is progressively reduced in all scenarios, but for different reasons. In Baseline, the strategy is not to expand the district-heating network, reducing the installed capacity, mostly CHP based, in which the thermal to electricity ratio is lower compared to 2015 for maintaining the electricity production roughly equal to the one of 2015. Scenario S1 mostly maintains a similar heat and electricity production to the one of 2015 that, considering the reduction of thermal demand, corresponds to a significant network expansion. The total installed capacity is lower, mostly reducing heating only boilers (but in quantity to cover peaks). Scenario S2, characterized by the lowest thermal demand and by higher environmental targets, cannot reach the emission reduction level with the proposed district heating technologies. Therefore, it reduces the district-heated area, but supplied with a cleaner and lower temperature network (Figure 6-25). Storage is selected in all the scenarios, highlighting its key role in the future energy system. This is perfectly in line with the results of Chapter 5.

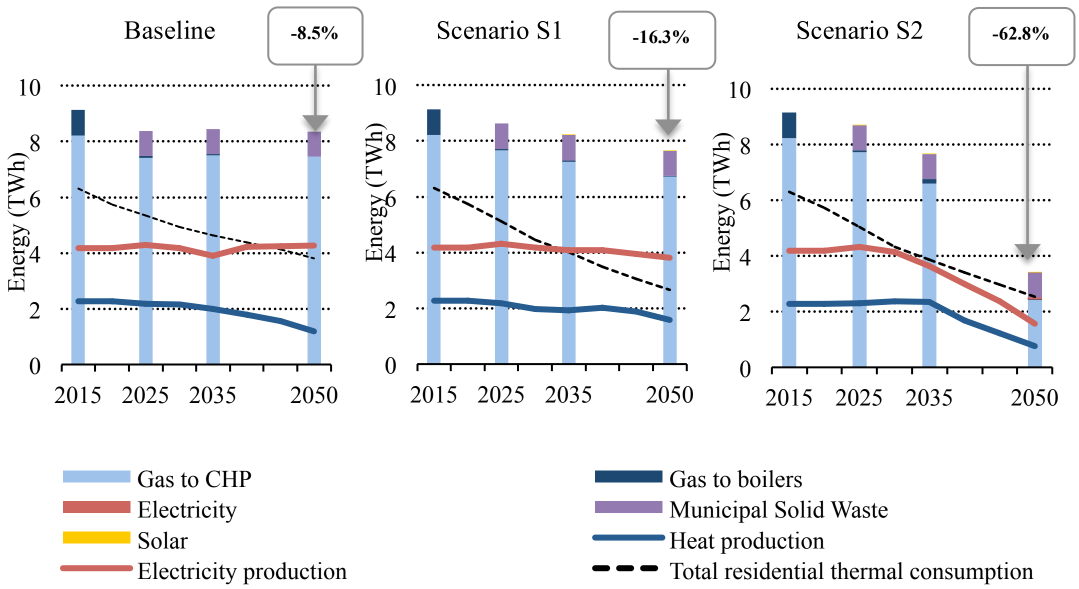

Figure 6-24: Total consumption of district heating system.

Table 6-9. District heating consumption, production and installed capacity.

	Base Year (2015)	Baseline (2050)	S1 (2050)	S2 (2050)
Total DH consumption (TWh)	9.14	8.36	7.65	3.4
Electricity Production (TWh_{el})	4.17	4.27	3.8	1.55
Heat production (TWh_{th})	2.27	1.2	1.58	0.76
Total Installed Capacity (GW)	2.19	0.77	1.21	0.51
CHP (GW_{th})	0.740	0.440	0.620	0.210
Large scale HP + solar (GW_{th})	/	/	/	0.05
HOB (GW_{th})	1.025	0.08	0.24	0.13

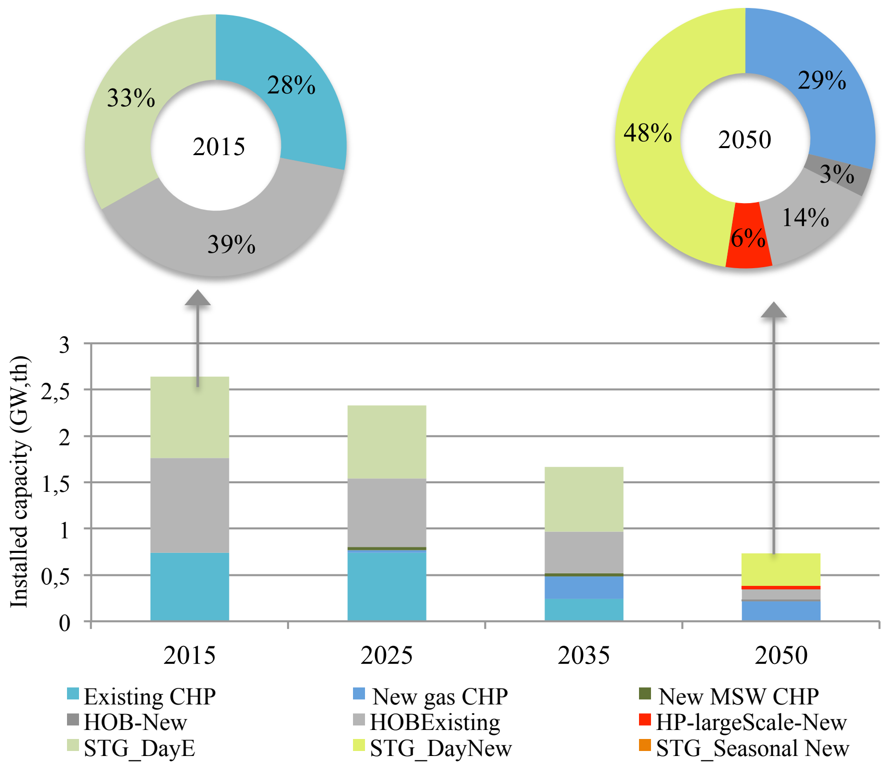

Figure 6-25: Evolution of the total installed DH capacity for Scenario S2.

Clearly, the end-use space heating technology mix changes as well. The mix of technologies changes according to what previously said on district heating, electricity and gas penetration (Baseline mostly relying on gas, Scenario S1 mostly relying on district heating and Scenario S2 in which heat pumps starts to penetrate with a significant share). Some common trends among scenarios are visible with respect to how the new capacity penetrates in the different residential building types (Figure 6-26): heat exchangers are present in compact buildings only, high efficiency pellet stoves are selected for single family only and heat pumps are selected for single families and new buildings only after 2030.

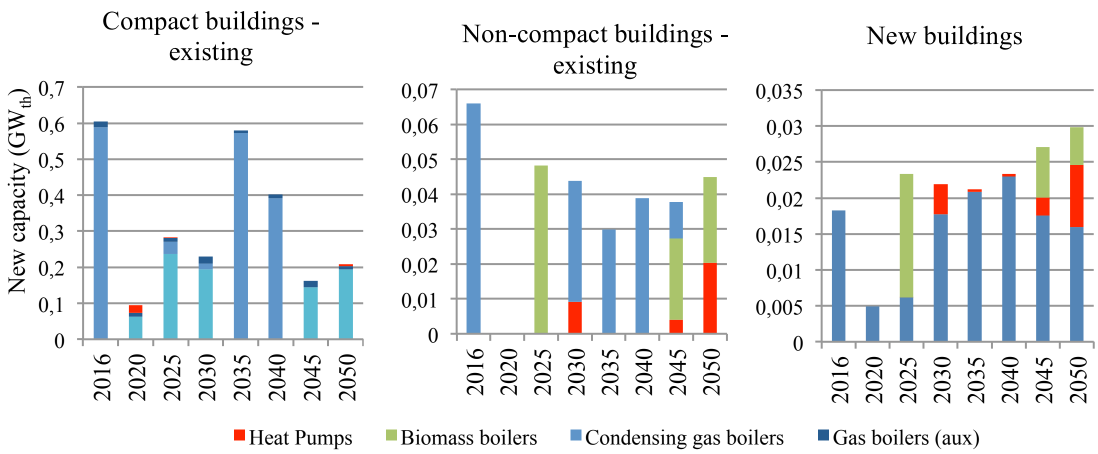

Figure 6-26: New capacity installed in the different building types for Scenario S2.

Figure 6-27 shows, as previously highlighted, in all scenarios, that renewables play an important role in covering energy needs when an emission target is fixed. In particular solar PV, solar thermal panels, MSW and biomass play a major role. In 2050, 2.7 Mm^2 of solar rooftop PV, 0.001 Mm^2 PV land (170 MW) and 0.98 Mm^2 thermal solar panels (57.2 MW) would be installed in Baseline. These values do not change significantly among the scenarios, with the exception of Scenario S2 where an additional 0.001 Mm^2 thermal solar land panels would be installed. In 2050, solar PV would cost-effectively cover roughly 12.5% of urban yearly electricity demand in all scenarios. Solar thermal panels would cover in 2050 hot water heat production for 325 GWh, covering more than 60% of water heating needs. This high penetration of solar technologies is hard to be effectively achieved considering land occupation difficulties and the visible impact of rooftop installation.

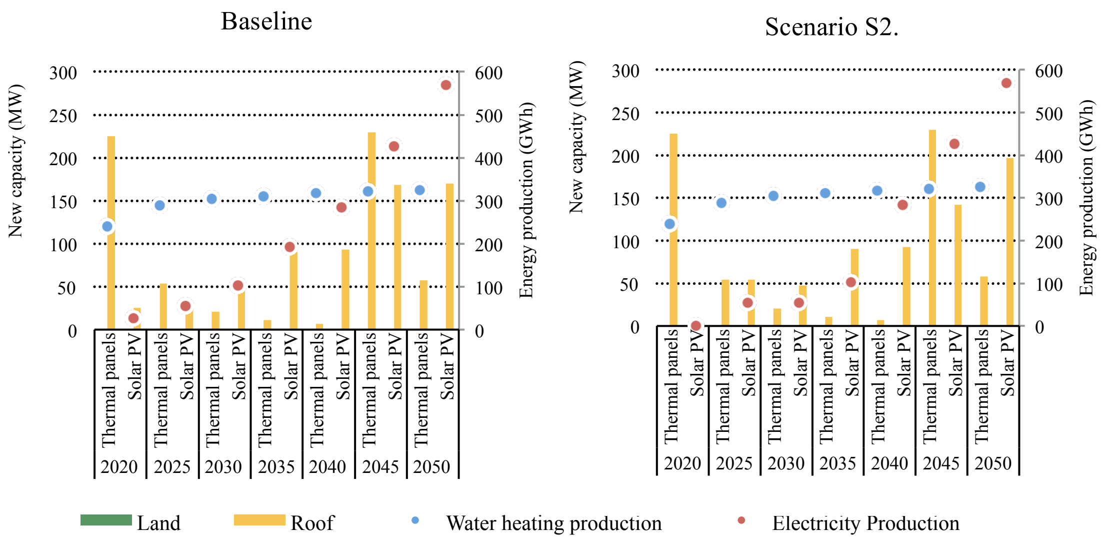

Figure 6-27: Newly installed capacity in solar technologies.

6.4.4 Financial evaluation to support decarbonisation

In Figure 6-16 the total system cost for the three different scenarios is shown. As previously affirmed, the added required investments for decarbonization are almost offset by a reduction of O&M costs, making the cost difference comparable and reasonable (even if most of the investments would be needed outside urban areas for decarbonizing the power sector). With respect to Baseline, the decarbonization cost for Scenario S2 is roughly 20 €/t_{CO2} (€ per tons of avoided carbon emissions) while for S1 is negative. This section summarizes the previously highlighted comments by providing an overview of how investments (not discounted annuity to be paid in the year) are distributed in the time horizon. As a common trend among scenarios, it can be said that the model invests deeply in retrofit measures to reduce investments in low carbon heat supply options. To sum up, with respect to Baseline, Scenario S1 (Figure 6-28) invests more in building retrofit, including advanced measures, and district heating while Scenario S2 invest even more in retrofit (more advanced and starting earlier) and more in solar and heat pumps. The purchase of electricity-consuming equipment and lighting fixtures is the same in all scenarios (in particular LED lamps are always selected). Similar trends among Scenarios are also visible for heat storage and solar technologies that are selected in all the scenarios.

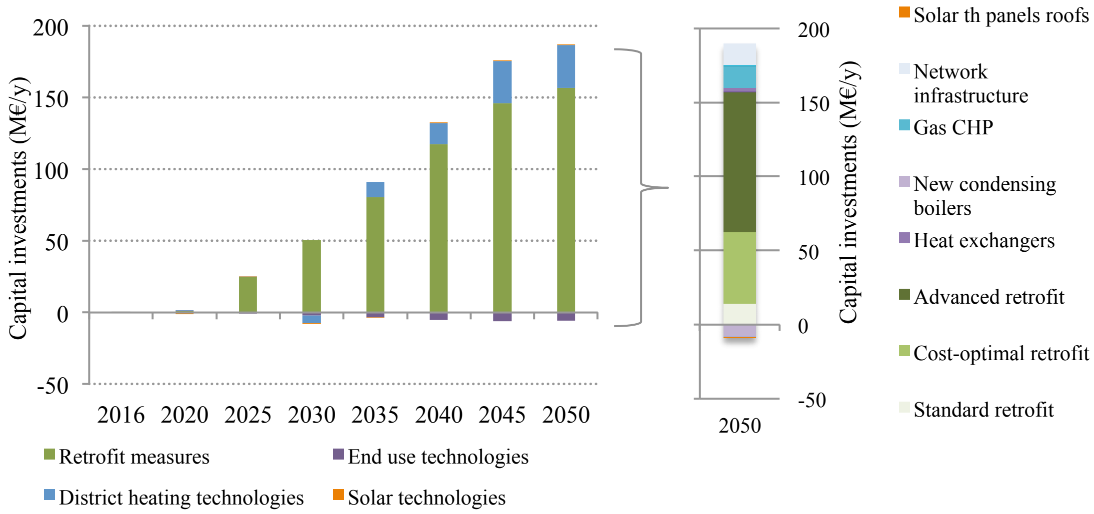

Figure 6-28: Annuity difference to be paid for investments between Baseline and Scenario S1. (not discounted)

6.4.5 Adding a carbon tax

A carbon tax was added in the Scenario S2, this scenario is identified as S2-CT. While a carbon tax and an emission cap have similar effects on the optimization, it was decided to test if the carbon tax does or does not influence technology choices in this context. In addition, in urban areas, few policies can be specifically defined, so this example shows that the model can also help in understanding the impact of external policies on urban areas. As it can be observed in Figure 6-29, by introducing a carbon tax, the urban consumption mix increases of 16.1%, shifting the energy system to rely mostly on decarbonized electricity (from 39.7% in S2 to 47.2% in S2-CT). In S2-CT, the total system cost is 2.71 billion € higher compared to S2, in which clearly major differences are in terms of variable costs (Figure 6-30); in scenario S2-CT, the decarbonization cost compared to Baseline almost equal the 2050 carbon tax being equal to 140 €/t_{CO2} (avoided CO_2). The principal impact of the carbon tax is related to a slightly reduction of retrofit measures (space heating intensity 18.95 kWh/m^3 instead of 16.69 kWh/m^3 of S2) in favour of a district heating expansion (adding +30 MW of large scale heat pumps and a new gas CHP, covering 25.7% of residential heating demand). To sum up, a carbon tax promotes a larger district heating network penetration and a consequent reduction of building retrofit, a reduction of individual gas boilers and an increase of heat pump penetration.

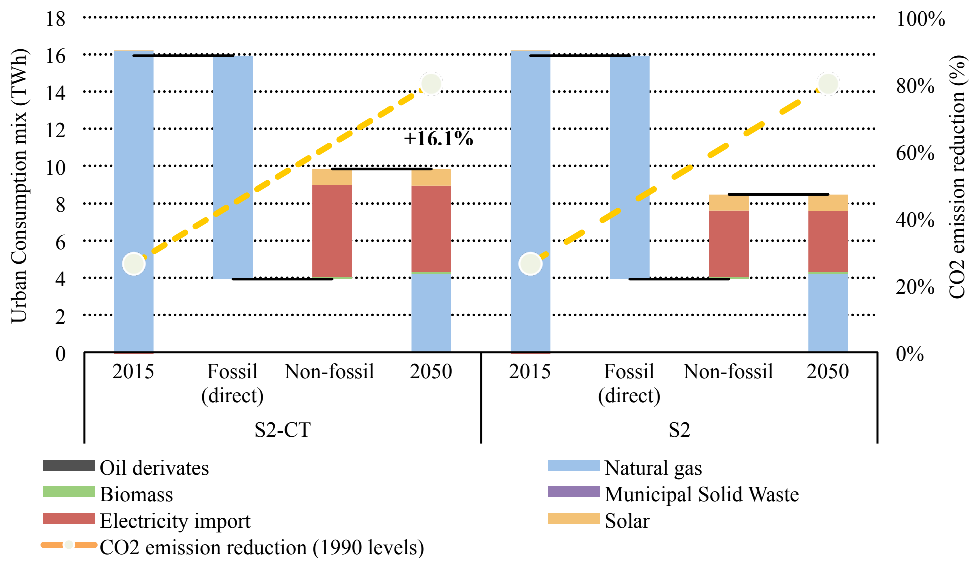

Figure 6-29: Total urban energy consumption for scenarios S2 and S2-CT.

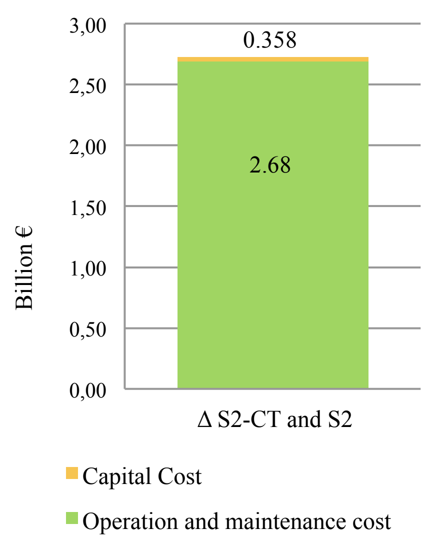

Figure 6-30: Difference in total system cost among scenario S2-CT and S2.

6.4.6 Fixing a district heating penetration level

The possibility to explore the impact of district heating network expansion as a part of the solution package is provided in this subsection. The proposed scenario S2-DH fixes a progressive bound on minimum and maximum heat demand supplied by district heating. In this scenario in 2050, the heat supplied by district heating is fixed between the 40% and 60% of total heat demand. Compared to S2, the total discounted system cost slightly increased by 2.11% (Figure 6-31b). Investment costs variations are mostly related to new district heating technologies and network expansion and to a lower amount to advanced retrofit measures. Electricity consumptions are lower from 2030 to 2040 mostly for the reduction of heat pumps capacity in the non-residential sector, but then in 2050, it is higher for the diffusion of heat pumps in the district heating system (Figure 6-31a and Figure 6-32). In this case, the target is met by roughly the same retrofitted volume, but accelerating the diffusion of cost-optimal measures.

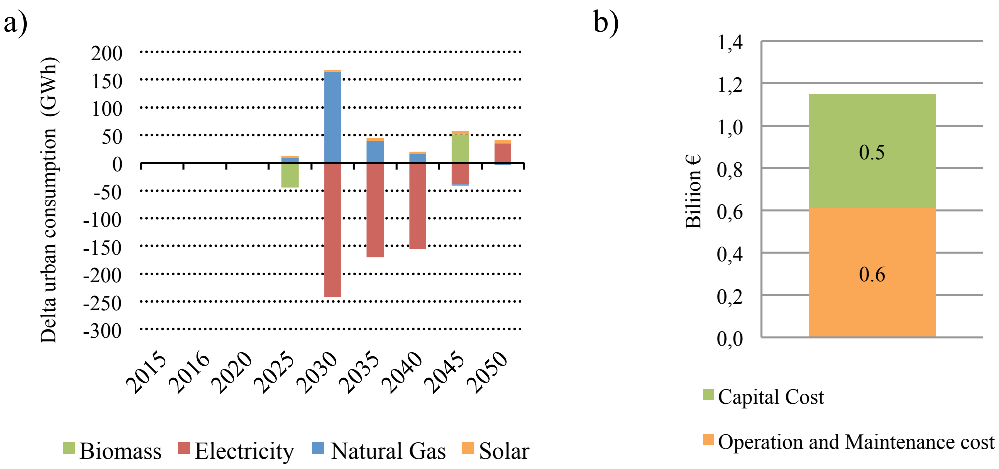

Figure 6-31: Differences from scenario S2 and S2-DH in terms of a) urban consumption and b) total system cost.

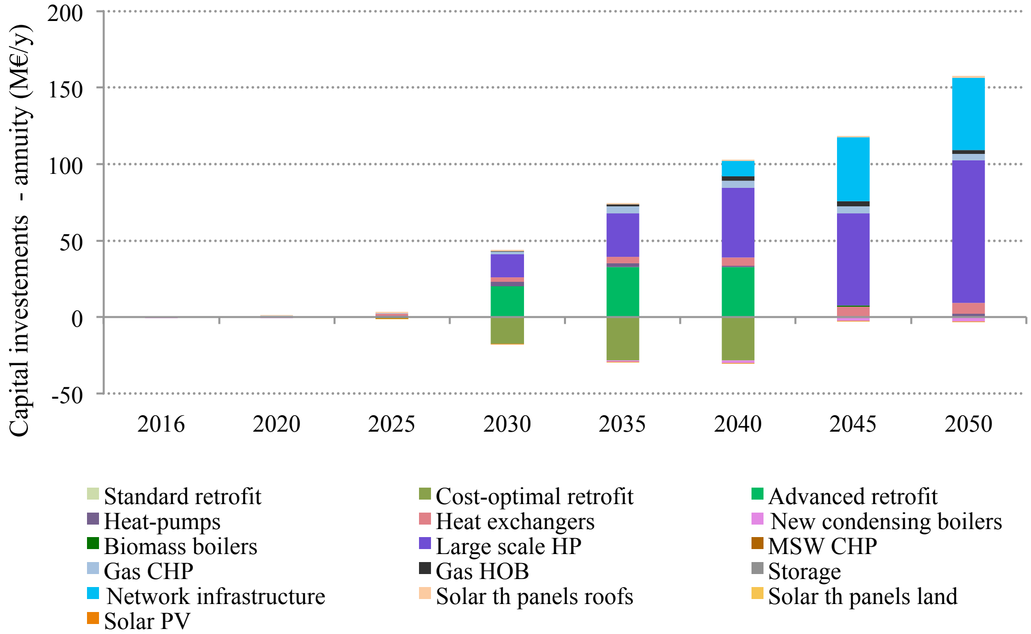

Figure 6-32: Delta investments in terms of yearly annuity (discounted at 2015 levels) from S2-DH and S2.

6.4.7 Removing the retrofit option

From the previously presented results, the building retrofit option has been consistently selected in all the scenarios, even if with different rates. From this consideration, it might results interesting to remove the retrofit option from the model reflecting what many planning models do on larger scales. Compared to S2, the total system cost grows of 3.25%, with lower investment costs (-6.2%) and higher variable costs (+9.2%). The decarbonization cost compared to Baseline is roughly 98 €/t_{CO2} (avoided CO_2). Total urban consumption is higher, clearly related to higher residential thermal needs (+63% compared to S2, Figure 6-33).

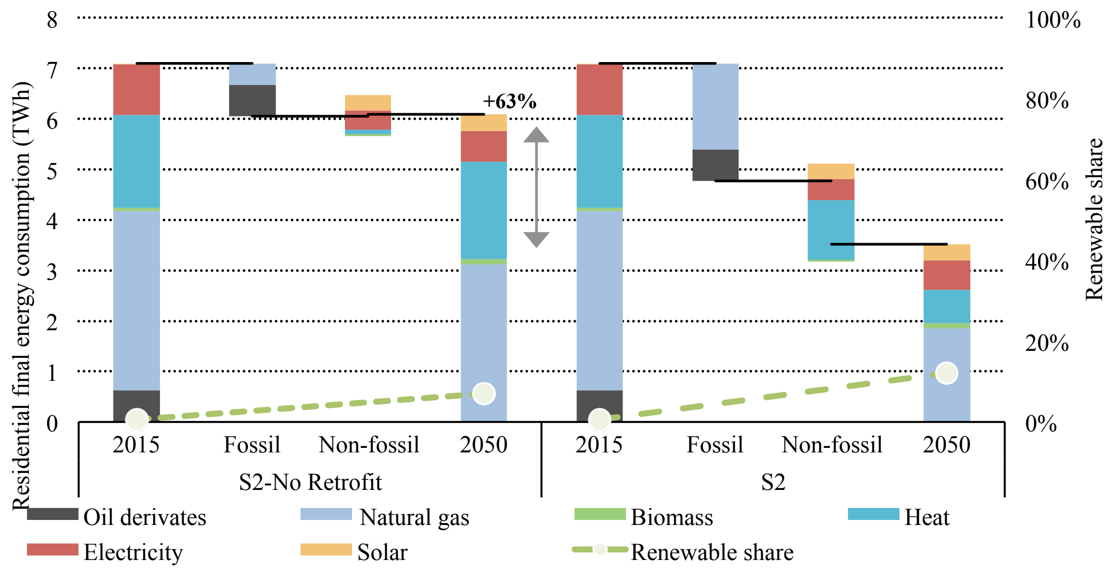

Figure 6-33: Residential final energy consumption with and without the retrofit option.

As expected from previous reflections, the role of district heating gains importance with respect to S2 (a significant part of the heat difference is supplied by district heating). In fact, the higher space heating demand of existing buildings is covered by 30.2% district heat, 56.4% gas, 7.1% electricity (heat pumps) and 6.3% biomass. The total district heated installed capacity is based on gas-CHP, large-scale heat pumps, storage and auxiliary gas boilers. Under this scenario, clearly, the dependence on decarbonized electricity produced outside the city is higher (Figure 6-34).

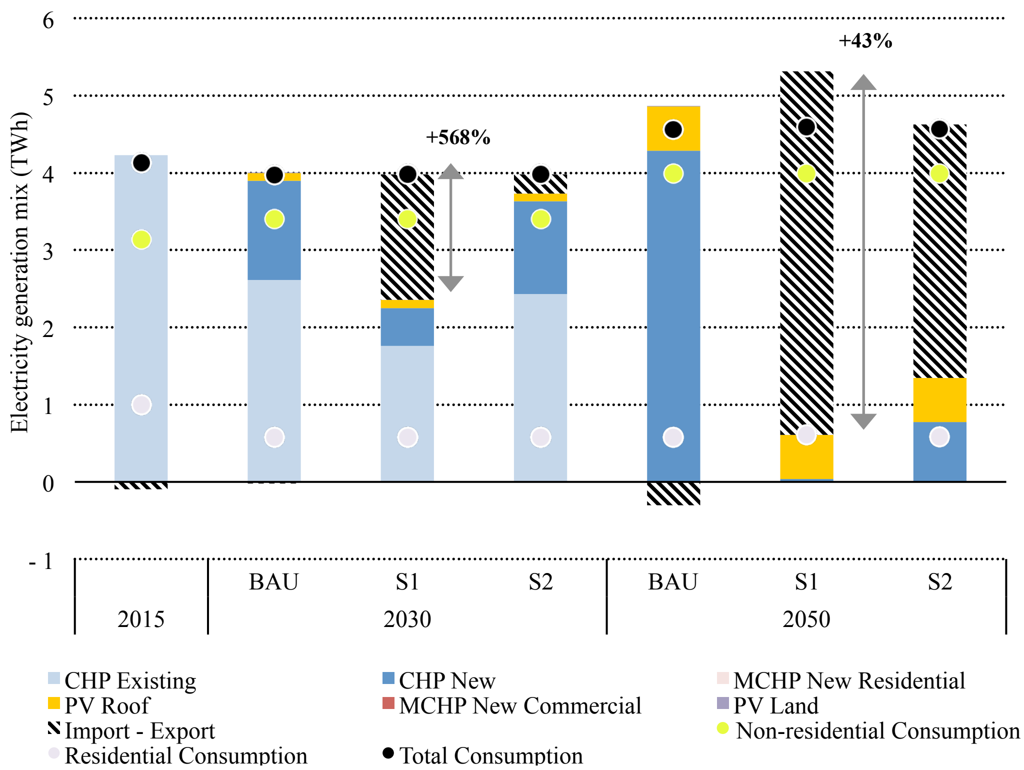

Figure 6-34: Electricity generation mix under different scenario assumptions.

From the results in this paragraph, interesting considerations may be derived. As previously explained, the cost for decarbonization in this scenario is higher (more than four times) compared to the one of S2, meaning that retrofit can reduce the decarbonization costs. More specifically, it provides opportunities for reducing and postponing the electrification process of end-uses (requiring the decarbonization of the power sector), opening wider options for the use of gas. Taking in mind that this results are also driven by the existing and proposed CHP technologies in the district heating network, that are assumed to work in back pressure mode, it can be said that in further works it might be interesting to variate this assumption. In particular, it might be interesting to study how the system would react if a greener gas network will be available, also when distributed micro-CHP technologies (also fuel cells based) enter in the competition. In this model, a run introducing micro-CHP was simulated, but it can be observed that the model does not choose these technologies, not fully commercially developed, also confirming that further sensitivity analyses on market access would be beneficial in further studies.

6.4.8 Uncertainties and sensitivity analysis

The scenarios analysis requires a specific focus on the elements of uncertainty. The focus of this study wasn't related to macro-economic drivers (population, GDP etc.), but rather on technology related aspects. Therefore, key selected uncertainties (Table 6-4) are analysed in this paragraph in which a sensitivity analysis is performed. The following uncertainties are selected:

- Discount rate: Low (3.5%), S2 (5%), High (10%);
- Bound on the maximum yearly penetration of retrofit measures: Yes (S2), No;
- Fuel prices: High, Low (S2);
- Decarbonization of the power sector: High (S2), Low;
- Bound on the minimum solar penetration: Yes (S2), No;
- Capacity bound on the maximum heat pump penetration: Yes (S2), No.

The impact of the variation of key uncertainties is evaluated on six indicators: total system cost, electricity to gas ratio, share of district heating covering residential thermal demand, penetration of renewables, renovated volume and share of cost-optimal measures. Results are shown in Figure 6-35. Among the considered variables, two have major impacts: the discount rate and the decarbonization of the power sector.

As it is clear, the total system cost is highly sensitive to the discount rate value (indicates to which amount future values are discounted at present level). At lower discount rates, the total system cost clearly growth (upfront costs for low carbon technologies), but the share of renewables diffusion result higher since also operational costs are included. A high discount rate reduces the selected renovated volume of roughly 12% because is capital intensive. A sensitivity analysis on the discount rate is very important for understanding the impact on system configuration, even if in this model only a part of the energy system is described. Another parameter to which the model is sensitive is the decarbonisation level of the electricity grid, in fact a lower decarbonisation of the grid made the energy system to rely more on gas and space heating demand results mostly covered by district heating, with a slightly higher total discounted system cost. The other variables taken into account have a lower impact on the considered parameters. As expected, higher fuel prices increase the total system cost and reduce the electricity to gas ratio. The share of district heating covering residential heat demand is also slightly reduced. If the bound of maximum heat pumps penetration is removed, the share of district heating covering residential heat demand increased, mostly covered by large-scale heat pumps. The share of renewables increases to cover the increased electricity demand for heat pumps. Removing the bound of maximum yearly retrofit rate doesn't impact on the selected retrofit volume, but it accelerates the penetration of retrofit measures. Removing the bound on minimum solar water heating production reduces the share of solar renewables and increases the share of electricity (high decarbonisation of the grid and low energy prices).

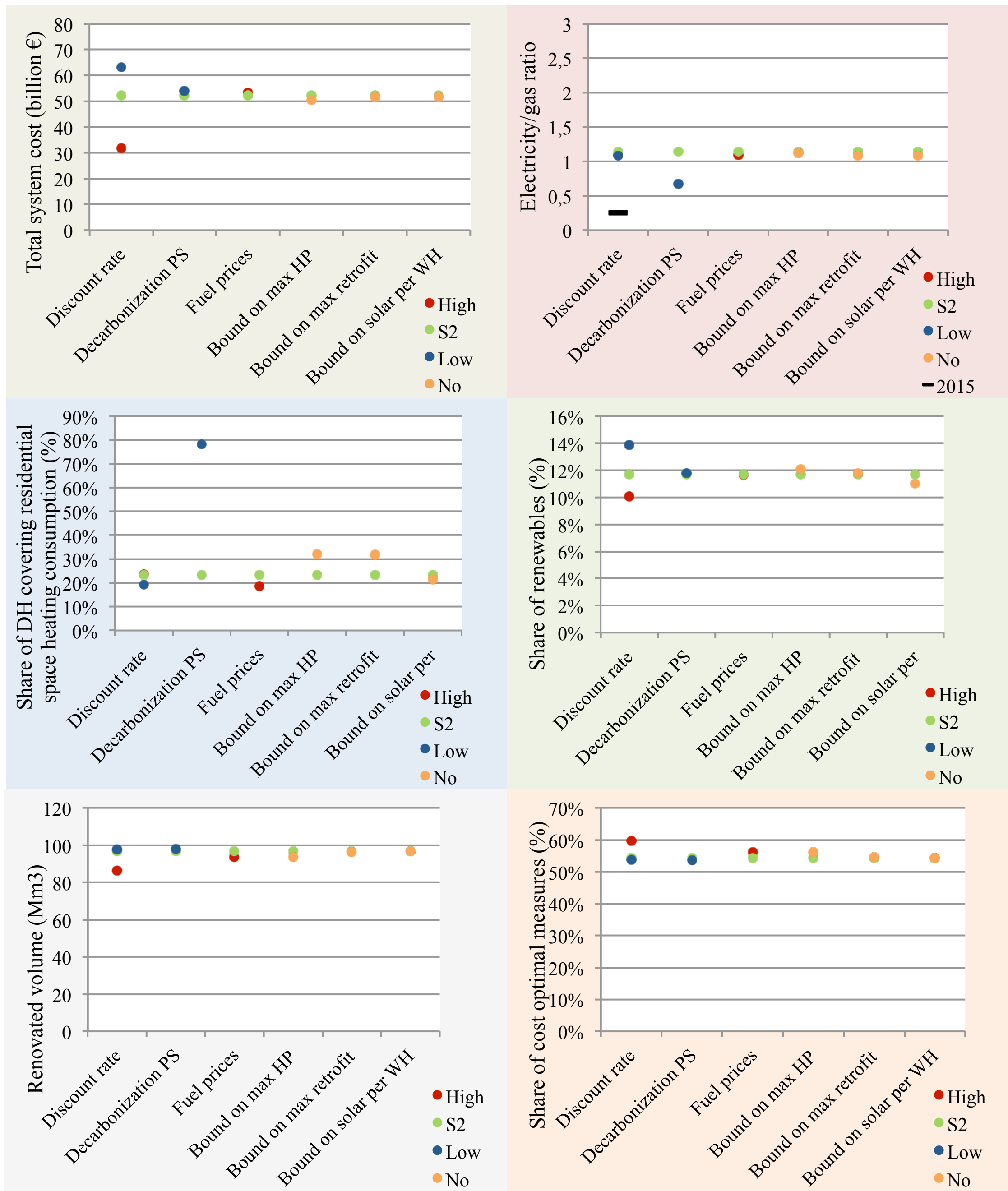

Figure 6-35: Sensitivity analysis.

6.5 Discussion

The presented model highlights that consistent opportunities are available in order to meet the decarbonization targets and contemporary provide improved building services at reasonable added costs. In particular, the scenarios undertakes an ambitious increase in energy efficiency and fuel switching from fossil fuel to renewable sources, highlighting that fuel switching and energy efficiency alone are not sufficient, but should be coupled with strong energy efficiency improvement in the end–uses (buildings, electric uses, and heating). Therefore, the CO_2 targets can be reached through a mixture of building retrofit measures (advanced in the later periods), solar PV and solar thermal, district heat from low carbon sources together with heat pumps, high efficiency gas and (for single families only) biomass boilers (Figure 6-36).

As previously observed, even if building retrofit diffusion may be limited by upfront costs, it covers a key role, reducing the costs for decarbonization, and it is consistently selected in all scenarios. In fact, retrofit measures to improve the performance of the existing building stock are needed, considering that most of 2050 buildings are already built today. This highlights the necessity of choosing cost-effective retrofit measures to be considered in the model. Clearly, to the resulted space heating energy savings correspond reduced investments in new capacity in the heat sector. In the heat sector, energy highly efficient technologies covered an important role, with increased penetration of renewables. As also emerged from Chapter 5, district heating strategies require coordination with energy efficient buildings together with a shift to low carbon solutions (integrating heat pumps, renewables and storage technologies). Nevertheless, this coordination should not be taken from granted being building retrofit linked to lower heat sales. Again, stakeholder engagement and new business models may avoid unnecessary high up-front investments.

Together with building retrofit, the key variable in this scenarios analysis is the decarbonization of the power sector, key pre-requisite to reach the environmental targets. This variable has driven an increased electrification of end-use energy services relying on decarbonized electricity from the grid. The electrification is visible mostly for the reduction of thermal needs and a slight increase of electricity demand (space cooling demand increases in all scenarios, while the reduction of thermal needs increases the electricity shares in end-uses), such as through heat pumps covering parts of the thermal demand (+80 MW new capacity in S2) and with a decarbonized power sector (indirectly catch in S1 and S2).

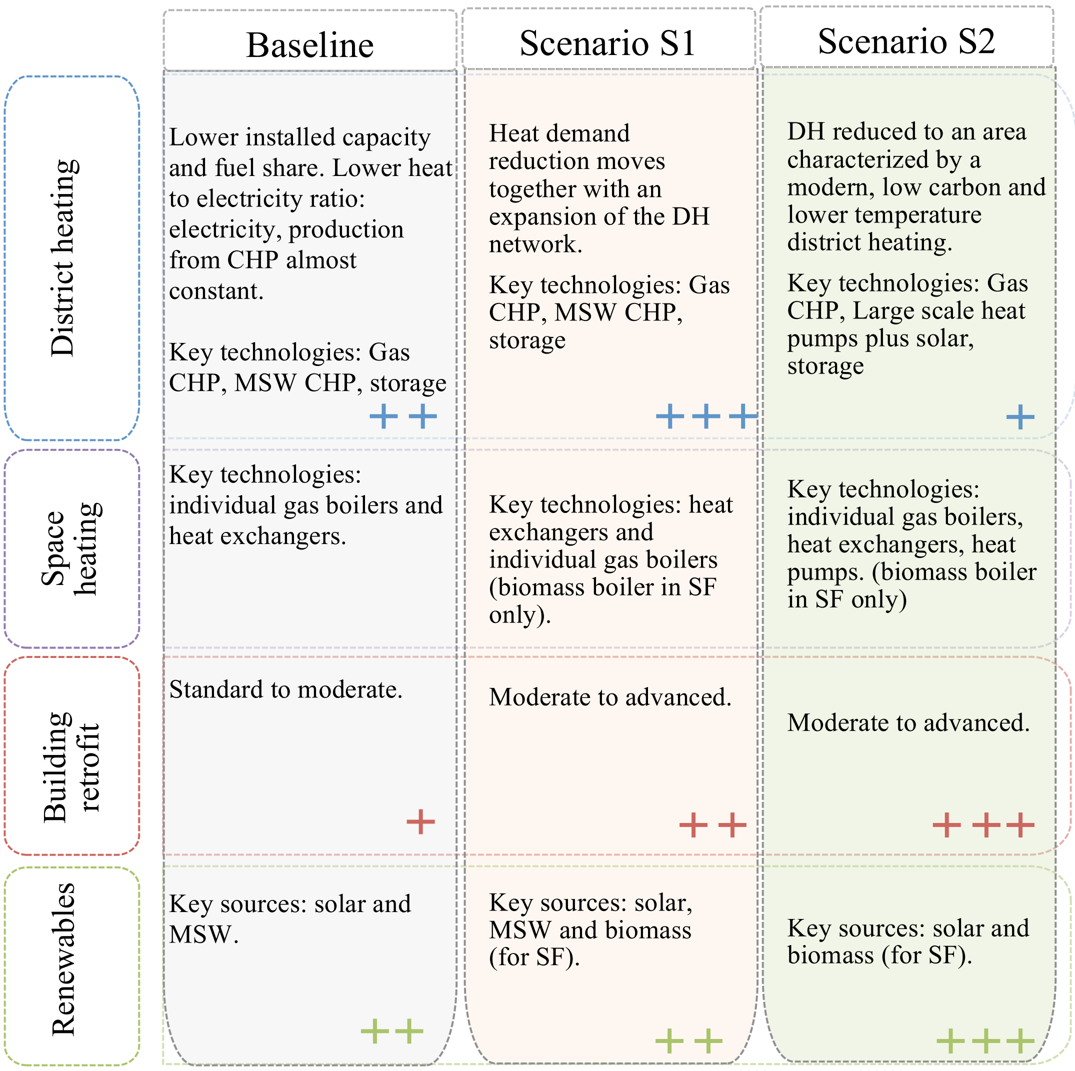

Figure 6-36: Scenarios key technological choices: summary. += medium importance; ++= high importance; +++= very high importance.

Interesting results emerged when the retrofit option was removed: the higher thermal demand was partly covered by district heating relying on large-scale heat pumps and by new individual gas boilers. This increased the electrification quota and also the costs for decarbonization. Even if the decarbonization of the power sector is likely to continue, building retrofit may, therefore, be seen as a flexibility instrument, slowing down the need of accelerating the power decarbonization process. This also opens interesting considerations for gas as a transition fuel, especially when the option of greening the gas network is taken into account. Even because, increasing the renewable share in urban areas is very challenging taking into account land occupation, few rooftop availabilities and the required ability to manage the variability in power variability.

From a methodological point of view, this approach results suitable for supporting the development of energy plans and for allocating demand-side/supply-side measures at an urban scale in which the decision variable is represented by the installed capacity (prescriptive investment optimization). This approach helps in creating technological pathways towards sustainable goal by means of a dynamic optimization among timeslices and time periods over the time horizon. Great attention needs to be dedicated to input data and uncertainties, in particular for an accurate description of the starting Reference Energy System and of innovative technologies not yet market-ready that tends to be excluded considering the high upfront costs.

Major limitations of this work, that will be further discussed in Chapter 7, are related to the fact that: (i) the model cannot catch the dependency of district heating network and variations in linear heat density; (ii) the low time resolution (40 yearly timeslices) is suitable for representing thermal variables (that can be simply stored), but may underestimate electricity peaks and the mismatch between energy demand and energy production, particularly important when describing electric renewables. This may require in further works to integrate different modelling frameworks for catching the interactions between heat and electricity and the related infrastructures together with solving the limitations related to temporal resolution. In addition, the scarce availability of non-residential building data resulted in a simplified description of that part of the Reference Energy System, requiring supplementary analyses in future studies.

Another aspect to be discussed is related to the fact that in urban areas local pollution is extremely important. In this model it was not evaluated and targeted since the mobility sector, which is strongly related to local pollution, is not modelled. Nevertheless, emission related to local pollution can be easily inserted into the model when required.

6.6 Conclusions

This chapter derives from the need of quantitative approaches to cost-effectively support the urban energy transition. The proposed model was developed for helping decision makers in understanding the actions to be prioritized during a certain planning time horizon. In particular, the target of the model is the decarbonisation of the heat sector, understanding the synergies between deep building retrofit and existing district heating systems within a broader energy system perspective.

Results confirm that deploying building retrofit together with low carbon technologies can reduce the environmental impacts at a reasonable added cost or maintaining a lower system cost depending on decarbonisation target. Providing a spatial representation of the urban environment and the building stock helps better understanding the building retrofit potential among the diverse building types and evaluating territorial constraints. Furthermore, it facilitates the evaluation of suitable areas for new technologies localization according to social, technical and territorial evaluations; very disaggregated results can be also disaggregated back on the spatial dimension. This option, as well as the model quality, is affected by the data availability. As described in Chapter 4, not all the necessary urban data existed, leading to highlight the need for thinking about new data collection and management protocols, improving data gathering capacity. This, again, will require the involvement of all urban stakeholders: better data can improve the understanding of resource availability and of building performances and consequently the measures to be pushed with priority.

Solar technologies play an important role: in general their deployment will depend on urban form and density, and the evolution of electricity grid as well. Bottom-up energy system models are functional for capturing these relationships even if with the proposed time resolution is more suitable thermal side analysis, being not detailed enough to catch the mismatch between demand and supply. The model confirms the achievability of an 80% decarbonisation target with known technologies. Further sensitivity analysis may be focused on understanding the role of technologies not yet fully commercially developed. In particular, other interesting future analyses may involve the understanding of the possibility of greening the gas network.

Chapter 7

Discussion

This Ph.D. dissertation is based on the observation that how to deal with urban energy planning in urban areas is a recent leading research topic with little agreement on the planning procedure, often based on short-term sectoral evaluations. In this picture, the thesis supports the definition of a methodological framework to harmonize the links between methodologies, belonging to different fields, in a coordinate whole to support urban practitioners and decision makers in their energy planning activities.

In particular, this thesis deals with bottom-up energy system modelling, territorial analysis and building physics to enhance energy planning practices at the urban scale. A wide overview of the state-of-the-art is provided during the thesis as well as a case study application for recognizing major advancements proposed in the thesis. This section highlights the major advancements as well as identified limitations in field by answering the research questions.

7.1 Research question answers

The conducted activities during the thesis generate outcomes that are further discussed.

- **Which are current and future challenges and barriers in long-term urban energy planning? Which can be a theoretical framework to support this practice?**

Understanding how to structure urban energy planning problems has been identified as a key necessity for the future of urban energy patterns. From the thesis, it emerges that **urban energy planning has to take into consideration an integrated approach**, intended as a procedure composed by several phases to combine existing methodologies in an agreed structure to enhance the quality and robustness of the planning results. In particular, the steps of the proposed procedure was firstly inspired by the one elaborated by (Mirakyan et al., 2009), while the combination of methodologies was analysed during the thesis focusing on the Preparation and Detailed Energy Modelling phase. The thesis was therefore focused on the steps to follow and on the methodologies to choose in order to develop robust scenarios (combinations of actions and measures) and to provide to stakeholders the elements for excluding the options that are not suitable for the specific urban areas in terms of economic, environmental and energetic considerations. The choice and prioritization of scenarios is further performed in Phase III of the procedure (Prioritization and Decision Making) where other "more qualitative" criteria are added to select the scenarios to implement in the energy plan. The key benefit of the proposed approach is related to the possibility of arriving at the Decision Making Phase with scenarios already skimmed and allowing to catch the interaction between the energy system, the environment, and the economy and to stress the integration between demand and supply. Among the multiple options of methodology combinations, four crucial points emerged:

- All the planning phases are fundamental to correctly fulfil the process and it should be avoided to go directly from the Preparation Phase to the implementation stage. The thesis introduced the importance of disposing of quantitative tools and methods to define the actions in a structured way before they enter in the Decision Making Phase. In this way, the scenarios are robustly selected and analysed before entering their prioritization process where other planning aspects (social, cultural preferences, etc.) are introduced;

- The involvement of stakeholders is key to the success of the energy planning procedure: they speed the data collection process, support the definition of the assumptions and of a shared city vision (**qualitative evaluations**). In addition, their role will be crucial in the definition of the prioritization criteria in the Decision Making process leading to the selection of scenarios;

- **Spatial analyses** are fundamental in urban planning (data collection, physical constraints). The Preparation Phase needs to be integrated with all the other phases in a spatial framework due to the necessity of handling a large volume of data to considerably improve the quality of planning and decision-making processes through intuitive visualization maps.

- **Comprehensive energy system models** resulted in a strong support for urban scenario buildings and are necessary at the planning stage of Phase II to quantitatively consider interactions among sectors and demand and supply options over the long term (**quantitative evaluations**). In Phase II, it is possible to interlink to comprehensive energy system models more than one method when it is deemed necessary;

Phase III (Prioritization and Decision Making) wasn't analysed in this thesis, but it can be supported by Multi-Criteria Analyses (InSmart, 2015). In this way, the alternative strategies derived from Phase II are outranked to define the planning strategy. By applying Multi-Criteria Analyses, it would be possible to take into account both quantitative and qualitative aspects, considering all sustainability pillars and expressing different and conflicting objectives or exploring the different aspects that can influence final decisions. A specific Section on how to connect the work presented in this thesis to the decision-aiding phase is further detailed in Section 7.2.

In addition to these general considerations, while performing the Detailed Energy Modelling Phase, some reflexions emerged to improve this Phase of the energy planning procedure in further studies. In particular, the reflexions involve the **low time resolution** (maximum at hourly level) and **level of aggregation** (macro-areas and archetypes) that characterize comprehensive energy system models. Taking into account the planning (and not design) purpose of economic-engineering models, the time resolution is not a problem when resources can be stored cost-effectively and, therefore, the mismatch between demand and supply is not causing errors in the evaluations. On the other hand, when the commodities cannot be stored easily (i.e., electricity), a higher time resolution would be beneficial to better understand peaks and the mismatch between demand and supply. A low time resolution may lead to underestimate peaks and consequently the role of storage or management measures or to overestimate the demand covered by renewables. Nevertheless, these models are adopted for energy planning (pre-design) and while moving to the design phase they will need to be combined with other operational modelling frameworks to solve the temporal resolution problems and to better catch the relationship between heat and electricity systems or infrastructure evolutions. This may lead to a **bi-directional flow of information between planning and operational models** highlighting a first future challenge related to the **interoperability of models**. Taking into account the increasing weight of renewable power generation as a clean energy source, power system models and energy system models will be increasingly connected.

From this specific need, Figure 7-1 extend the energy planning procedure as proposed by the energy intended as a process characterized by (Mirakyan et al., 2009) by dividing it into the interrelated **planning and operational stage**. The planning stage includes Phase I (Preparation), Phase II (Detailed Energy Modelling with Comprehensive Energy System Models) and Phase III (Decisional Process) which major actions can be summarized into: knowing / understanding / planning/ prioritizing / deciding to be iterated, repeated and improved during the process. From the planning stage, a strategy or "energy plan" should emerge. This step is crucial to further proceed with the operational stage that involves the implementation of the energy planning strategy by designing / acting / monitoring / informing. This may involve the re-disaggregation of the planning results on the spatial layer and the project detailed definition. New obstacles or barriers can be found in the design phase requiring re-defining the strategy itself and coming back to the planning stage.

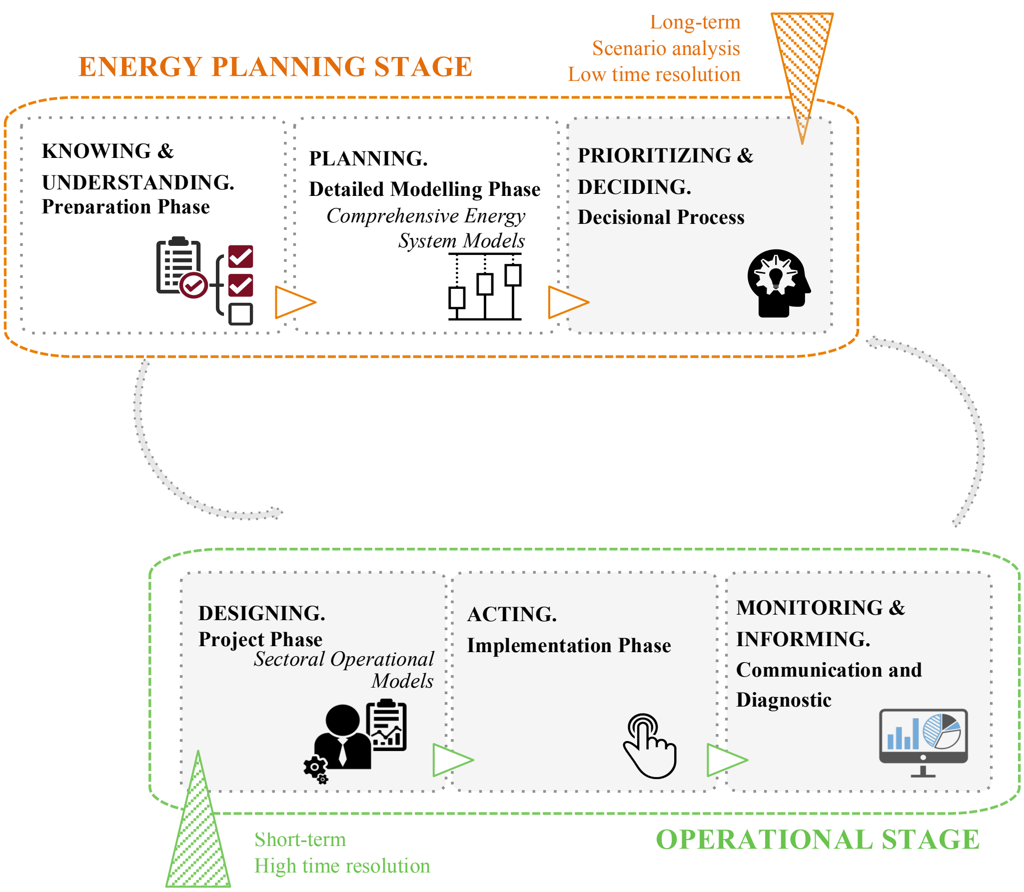

Figure 7-1: Proposed framework to perform the urban energy planning procedure.

Nevertheless, as previously declared, an integrated energy planning approach is far to be common practice and particular several identified barriers will need to be faced:

- The need of changing **traditional thinking and habits** that may lead urban actors to be discouraged because this approach necessitates integrating a wide range and diversity of disciplines. It may require a radical change in the traditional planning practice, requiring new competencies and additional people to perform it.

- The required time to perform the complete planning process (**time-consuming**). This involves both the time to collect, manage and organize data as well as in performing the analysis itself; time that technician of the municipality or decision makers may not dispose of, due to all the complementary “practical and bureaucratic” activities to be concluded and/or the short administrative mandate.

- The required **costs** related to the necessary **high level of expertise** to use and combine the different methods as well as the costs to develop/buy/maintain software and hardware. This may open a debate whether competences need to be inside the municipality or provided by consultant or the planning process committed to academia/consultants.

- The need for **high-level data** (quantity and quality) and **expertise for the assessment processes**. The availability and reliability of large standardized databases and public data sources are currently limited at the local level, limiting the modelling choices and requiring high efforts from local stakeholders. This issue is very challenging since the data is not always open-source and updated, as will be further discussed in the next paragraphs. Furthermore, the data collection process requires new instruments (e.g., smart meters) and new physical resources to analyse them, often not a priority taking into account the limited resource availability in local municipalities (especially if very small).

- The necessity of **transparency** on input data, assumptions and results as well as to **synthesize** the planning procedure in to be **understandable to decision-makers**. This fact is crucial since it provides new opportunities for collaboration between non-experts and experts.

Another emerged challenge is related to the introduction of the **human dimension** (both as stochastic inputs related to the occupant behaviour theory and as willingness to invest in new technologies).

Overcoming the existing barriers and challenges would complement and enhance the methodology applied in this dissertation, which already provides, in the first instance, a useful approach to assessing prospective pathways forward for integrated energy planning. The proposed methodological framework is built upon existing methodologies to deliver a first-level assessment of the appropriate combination of methods within a more integrated energy system planning.

- **How to "adapt" long-term comprehensive energy system methods and tools to urban applications?**

The family of comprehensive energy system models is broad and, in the thesis, two examples of simulation and optimization models were proposed. While there is not a single model fitting every reality, some criteria to select the comprehensive energy system model/tool in urban areas are suggested. They are:

- Time horizon: a medium/long-term time horizon is suggested;
- Time resolution: a low resolution is fine when the focus on thermal energy consumption, while a link with operational models is necessary when analysing renewables or electricity-based technologies;
- Flexibility in building the model: a high level of flexibility is required for structuring the model, in particular for modelling both demand supply side and guarantying a high disaggregation level of the demand and a good technological description (possibility to deep on the single object such as hospitals or power plants). Attention that while a higher disaggregation could help in better represent the energy system, it also may impact on the adaptability of the modelling structure to other realities;
- Possibility to soft- or hard- linking with spatial tools: as already stressed, the role of spatial analysis in local applications is essential;
- Possibility of performing energy, environmental and financial evaluations: energy planning should not neglect these three dimensions of sustainability. Important also the possibilities of incorporating the human dimension.

Nevertheless, as previously highlighted, comprehensive energy system methods and tools are extremely effective for planning purposes, but cannot be used alone for urban applications and should be combined with other methodologies. This is mostly related to the need of disposing of a **detailed and highly disaggregated description of the demand** and of the **spatiality** to deal with specific urban needs (critical areas, liveability, built environment constraints).

In particular, in the proposed methodological framework, two crucial integrations are highlighted:

- The adoption of Georeferenced Information System is fundamental for the preparation of a supportive database allowing managing and visualizing the territorial and socio-economic spatial peculiarities (Phase I). Furthermore, it is functional to calculate important information on urban form, building distribution, street/infrastructure layouts and it may also be functional to the re-disaggregation of planning results;

- A detailed building physic-based description of the building stock, as the proposed one, has multiple advantages such as: a better estimation of the building load and its evolution (retrofit analysis); the possibility to differentiate retrofit measures, technologies and costs according to the real conditions of the building (e.g., low temperature heat generation systems not compatible with old heat distribution systems) or in perspective, to the building types (deep retrofit rates are lower in high-rise multi-property buildings);

- In addition, in future studies, a link with infrastructure models can provide additional advantages to the procedure. In this way, both new constraints related to infrastructure capability and compatibility and/or the impact of new investments on the infrastructures can be further explored.

Nonetheless, while this thesis was mostly focused on the aspect of heat decarbonization (concentrating on buildings, heat and power), it should be stated that urban energy planning goes beyond this topic, being a much broader "integration" issue. In fact, an urban energy system is composed by interlinked components and networks (buildings, transport, industry, heat and power, waste and water), whose interactions need to be understood during the energy planning practice. Adding all the urban sectors can certainly provide a broader overview of solutions, supporting the allocation of economic resources in the energy plans. Here the author aims to concentrate on the interrelations within the building and heat sector when other sectors are added in the modelling framework.

While the building sector was deeply analysed in the thesis, greater integration aspects can be introduced in this sector as well and it may be interesting to deep its potential links with other sectors. As an example, from the thesis, it appeared that solar PV could contribute to the generation of electricity in urban areas even if limited by building density; by the way, the results can be further detailed by adding links with urban master plans to integrate PV in new surfaces (e.g., façade-integrated PV may provide a contribution, worth to be investigated in further studies). As another example, further explained in Section 7.2, the surplus of renewable electricity can generate backflows in the grid, providing opportunities for electric vehicles charging/power to gas conversion/heat pumps utilization. The use of wastewater sludge for producing syngas to be injected in the gas grid can represent another interesting link. Together with buildings, urban mobility is another key sector with large opportunities and low carbon measures portfolio (e.g. the shift in transport modal choices and the promotion of low carbon vehicles, even if personal mobility if highly dependent by individual lifestyle). An example of a link among transportation and low-grade heat generation is represented by geothermal heat sources in metro systems as presented by (Barla et al., 2016; Barla and Donna, 2016). This heat can be exploited by heat pumps to raise their temperature. Moreover, while industries are in typically concentrated outside urban areas, some industrial activities are present within the city. In this case, industrial activities located in urban areas may provide integration possibilities with respect to waste heat (in DH if close to it or in nearby processes) and renewables (detailed energy data are sporadic while indications of the respect of air quality limits can be much easily available). Waste management can also be connected with heat networks (as with incinerators) and can be further explored. In fact, MSW together with geothermal and solar energy are most energy sources present inside the city, even if limited by available installation areas.

Therefore, new opportunities of integration need to be further studied for a complete energy planning approach, considering the available potential options (e.g. distributed PV coupled with heat pumps or electric vehicles or low temperature district heating and cooling). The bunch of possible solutions as well as the links between sectors are strictly dependent on local peculiarities (climate, economic level and structure, soil disposal, built environment age and building and people footprint) and cannot be generalized. As an example, the integration of district heating and cooling is easier in cold climate and high-density cities.

In the process, not only new sectors and technologies but also new material and commodity flows can be introduced. As a relevant example, maintaining a good outdoor and indoor air quality level is essential for the health of urban citizens. Ambient air pollution derives from multiple sources (e.g., fuel combustion in building plants, vehicles, power plants etc.). In this thesis, the air quality aspect was not included since the mobility sector (one of the principal contributors) was not part of the modelling activities possibly leading to wrong recommendations if inserted in the optimization. Nevertheless, air pollution (in terms of yearly emissions and not air concentration) can be easily added in the modelling framework both as an optimization constraint and as an additional criterion of evaluation.

An example of how the integration can be performed can follow the same path as from Chapter 5 to Chapter 6 (from heat to the whole building services), further extending the Reference Energy System.

- **Which are the strengths, weaknesses and main opportunities of the two main comprehensive energy system method/tool families (simulation and optimization approaches) in urban applications? How to couple them with building energy modelling?**

In the thesis, both simulation and optimization approaches were tested. As a result, none of them better fits the urban energy planning procedure, but both models have demonstrated to be suitable for supporting urban energy planning depending on the planning question to be answered. Simulation models are descriptive and should be used to explore what will happen if an energy plan is implemented by providing "snapshots" of different energy system configurations and their impacts. The application of simulation tools is mainly concentrated on feasibility studies, including renewable energy applications, distributed generation and smart micro-grid with a higher time resolution compared to the optimization ones. Optimization models are functional to generate the energy plans and to allocate economic resources among demand and supply; they are dynamic among timeslices and time-periods. They are mostly used for creating long-term investment strategies to fulfil government targets at the minimum system cost. In this case, the time resolution is usually lower in comparison to simulation tools. In **Figure 7-2** main information about the approaches is summarized.

For the author opinion, the choice of the approach mostly depends from the:

- Stakeholder involvements and availability to be involved in the process: with a high stakeholders availability simulation approach may be more intuitive and easier to be effectively managed (considering that all the analysed options are exogenous) while the optimization approach may provide more robust results, but more challenging to be then disaggregated on the spatial layer and understandable to non-experts. Furthermore, simulation models may be more indicated when specific options (e.g., not yet competitive) need to be tested;

- Objective of the analysis: optimization approaches are suitable for understanding how to reach a certain target and to support energy policy analyses while simulation ones are more suitable for comparing different alternatives and testing their feasibility;

- Desired outputs: optimization approaches provides a wider range of results, being dynamic over the whole time-horizon and searching for a lower cost solution. On the other hand, simulation approaches can go more in detail in temporal resolution and allows testing particular solutions that would be excluded in an optimization framework

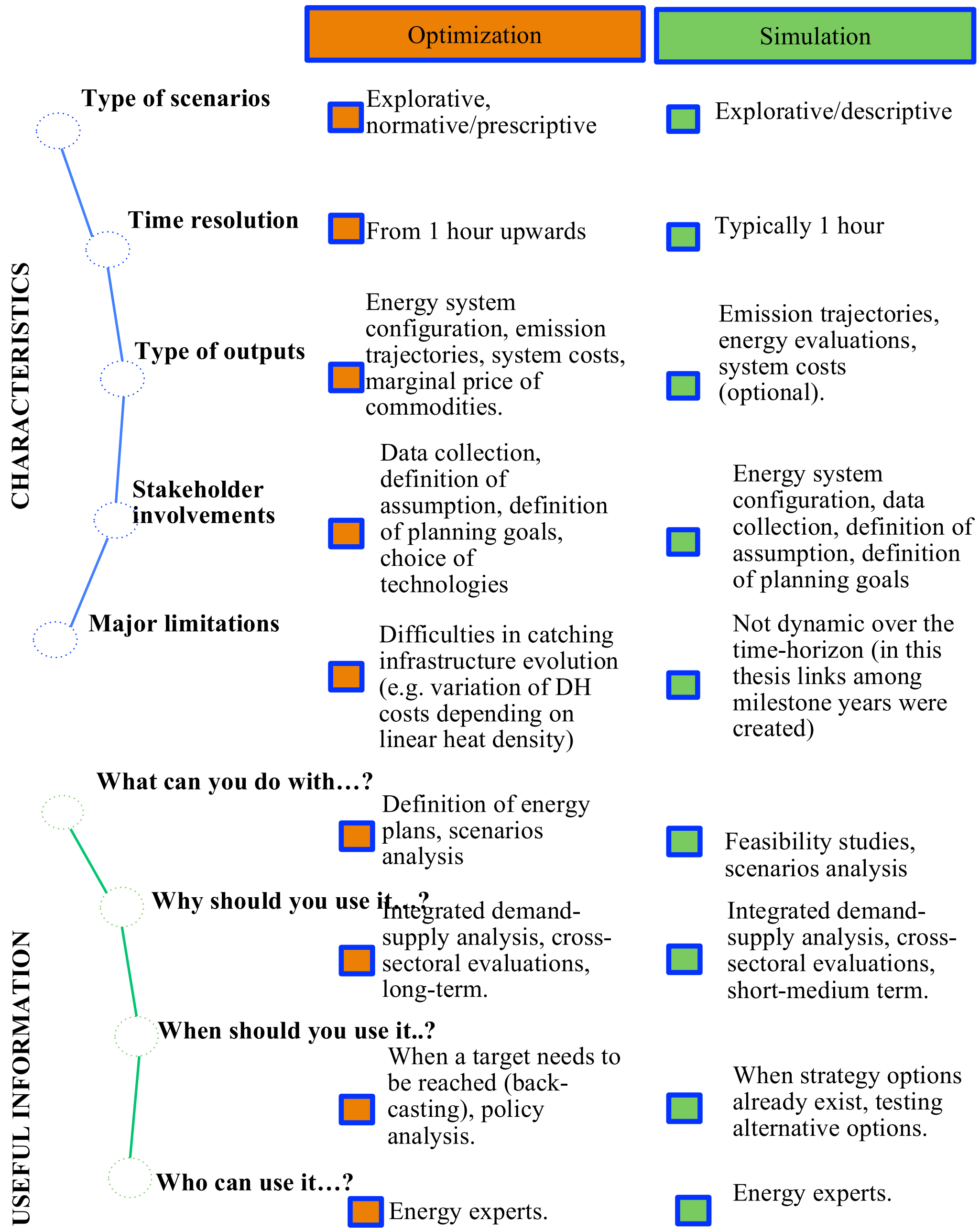

Figure 7-2: Summarized information related to the simulation and optimization approach.

As observed, building energy modelling - in particular for retrofit analyses – is fundamental for urban applications. For urban analysis in general, the two most suitable approaches were identified in the regression and archetype methods. The choice between archetype and regression methods mostly depends on data availability (i.e. structural data for archetype and real consumption data for regression) and the willingness to explore retrofit solutions (archetype) or to forecast energy consumption (regression). For planning purposes, the archetype method resulted to be the more appropriate to be coupled with comprehensive energy system models for two main reasons:

- It allows buildings to be aggregated into "Reference Buildings" with characterized energy service demands directly representable in the Reference Energy System;

- It enables simulating several retrofit options to be included in the planning analysis. It is extremely important to previously select the retrofit measures to be inserted in the model, in this thesis - for example – the cost-optimal approach was proposed.

The specific need of using the archetype method to link building energy modelling with comprehensive energy system models does not limit the possibility to have a more detailed description of urban buildings by applying other methods for the characterization of energy demand. In this case, a very detailed data-driven description of the building stock can provide to the energy-planner two layers of information: building-by-building energy consumption helpful for including micro-climate and urban form information, real-time diagnostic, demand-side management, etc.; and these data aggregated in archetype as planning support.

As described, the models' structure is unavoidably dependent on data availability and quality. In this thesis not all the necessary data were present, requiring the definition of numerous assumptions. A brief discussion on how data availability impacted on the methodology, its limitation and how it may be improved is further provided.

As a first observation, the energy balance of the city was dated 2005 requiring to be updated by the author taking into account the new building distributions and the expansion of the district heating network. This fact may impact on the potential mismatch from what is modelled and what really happened in the city from 2005 to 2015 regarding the energy mix. Together with a more frequent update of the energy balance, allowing users to access the urban energy plant cadastre, even at an aggregated level, can strongly improve the description of the energy mix and consequently the Base Year RES. Another improvement can be associated with the building energy demand and consumption profile description. As preliminary proposed in the thesis, the analytical approach provided by the archetype technique can be enhanced by providing regulated accessibility of a part of real energy consumption data (e.g., from energy utilities). In this case, data is very accurate (monitored), but privacy issues and lack of data exchange regulation might limit its access. Disposing of real data can improve the calibration of analytical models, but also can lead to a better building categorization and detail in the energy load profiles for the different Reference Buildings. In particular, the part related to non-residential buildings needs to be consistently improved, being most of the existing research focused on the description of residential buildings. This impacted on the simplified structure of the model for non-residential buildings (described per destination use and not per construction period, unavailable thermo-physical characteristics, energy and technology mix derived from energy balance calibration). Both the energy mix and the energy demand can be improved by the disposal of building energy performance certificates, which can be provided as additional information in a GIS platform. This may allow improving the spatial detail as well as the understanding of the energy consumption by fuel. In addition, this information may help to understand which of the buildings were already retrofitted. Improvements can derive also from the disposal of reference tabular data about technology costs, their efficiency and learning curves always very uncertain and derived from several sources.

A possible way to improve the data management and availability for planning purposes it to define common data protocol/packages to be filled by the different municipalities, together with the definition of data exchange standards. In addition, in future energy systems more and more distributed energy resources will be integrated with demand-side measures and demand management and response options. Administration may dispose of monitored data on the city system. This will enhance the quantity of monitored data and energy control options, having more precise information (temporal and spatial) of energy consumption, hopefully, be delivering a full description of the city consumption.

Toward this vision, more data-driven energy models can better represent the single building energy consumption behaviour, including more local aspects (e.g., street orientation, shading, vegetation, social dimensions, etc.). The very detailed building energy demand can enhance GIS platform to show real-time data that can then be re-aggregated to the archetype definition in order to be further used as input for comprehensive energy system models and identify “reference” retrofit measures. This higher level of detail will also help in the spatial disaggregation of comprehensive energy system model results (it can also be supported by a further regionalization of the model).

- **Are comprehensive energy system methods and tools suitable to support holistic heat decarbonisation strategies in urban areas (involving building retrofit and new heat generation technologies)?**

This paragraph discusses how the proposed methods, tools and methodologies can be applied to tackle the issue of heat decarbonization when a city is district heated and more widely in all the cities with significant heat needs. Starting from general considerations and concluding with the learning outcomes provided by the case study, the main limitations and generalizations of the proposed methods are further discussed.

Before discussing the general applicability of comprehensive energy system models on urban heated areas, it should be first stated that the proposed theoretical framework, summarizing the adopted procedure in terms of urban planning phases, can be used as reference for every local (intended as urban and regional) context. This means that the steps to be followed during a planning process are the same as the ones proposed in this thesis and can be followed in every city. What is very site-dependent is the network of stakeholders and the structure of comprehensive energy system models. In fact, they should be shaped to match the data availability and the specific planning needs, which change for every geographical and socio-cultural setting. The macro-approaches (simulation and optimization) can noticeably be replicated for every geographical area, but their structure is mostly dependent on: the climate (shaping energy needs); the city goals (environmental, social, economic objectives); the city priorities (are all the basic needs satisfied?); the city data availability (high or low level); the existing conditions (historical and cultural sites, infrastructure availability, expansion of the city etc.); the time evolution (rapid transformation).

A first distinction that emerges from the highlighted points is between developed and developing countries. The proposed application was explicitly shaped on a city in a developed Country, and for this reason, it is mostly replicable in European district-heated cities. Larger efforts would be needed to adapt it when moving into developing countries where both energy-service needs and priority, as well as the socio-economic dynamics and built environment evolution significantly change with respect to the ones analysed in this thesis, undertaking rapid transformations. In fact, in developing contexts the planning objectives are rather different with respect to the ones of developed ones: generating new services and well-being (and in some cases reliable energy access) with respect to sustainability targets, environmental protection and human development goals vs. maintaining/improving the service and life-quality levels while achieving environmental targets (air pollution, resource depletion and climate change). A very high potential is embedded in a correct planning of developing countries' urban areas, with large opportunities to plan components integration to leapfrog to efficient solutions. In fact, in this areas it is possible to build with already existing high efficient technologies, starting from the basic needs of people in the area to be prioritized with a larger citizen involvement (deep overlapping with social-sciences, cultural preferences and political capacity). With respect to the existing conditions, in developing countries, higher attention is devoted to "what is new" compared to "what it exists" (as in developed countries where high costs related to infrastructure modification can limit the options). A lower level of constraints associated with existing infrastructures and buildings is present; in fact ,the focus is more on building new infrastructures (distributed generation or more centralized systems?) and buildings (new building codes). In this vision, distributed generation, as well as new building codes, gains higher importance with respect to re-using existing infrastructures and buildings retrofit. Besides, developing countries are facing rapid transformations with proactive engagements with the private sector, introducing new business models. In addition to this, energy tariffs are rapidly changing and their structure is not well defined; furthermore, very localized database are rarely accessible or available and when they are, they are highly uncertain.

Even if the opportunities for energy system integration are more abundant, from these considerations emerge the limits of immediate applicability of data-intensive approaches on developing and rapidly transforming countries. Nevertheless, the approach is flexible enough to be specifically adapted and simplified to be applied as support, integrated with many sectorial models, for energy planning in developing countries: in this case, the author suggests a self-built simulation model rather than an optimization framework, where data uncertainty can lead to wrong recommendations.

In addition to these considerations, some general reflection on limitations on the applicability of the approach is further introduced. As observed, comprehensive energy system methods and tools offer support for deriving/understanding the mix of measures that fit, from an economic-engineering perspective, within a specific city context. From the viewpoint of heat decarbonization, this implies not only an evolution of the technology mix but heat networks as well (if present). To the evolution of heat networks is related the principal limitation of the approach: comprehensive energy system methods and tools represent the network as a "black box" and do not check the technical (physical/thermodynamic) feasibility of the new mix. The technical feasibility can be related to the variation of thermal losses, low vs.

high temperature networks, etc.., which also impact on the economics of the system. Partially, this can be solved with developing self-built methods (such as the simulation approach of Chapter 5) where some aspects can be embedded (i.e., the thermal losses variation together with the change of the thermal load), but at the expenses of other aspects (i.e., the possibility to manage lower assumptions and data). When using model generators (such as TIMES as proposed in Chapter 6), at first this issue can be preliminarily handled by disaggregating as much as possible the description of the network (e.g., separating low temperature and high temperature options). However, this problem can be solved by a post-run check of the feasibility of the new "system configuration". This check will require a spatial disaggregation of results and the definition of the new network layout (further discussed in paragraph 7.2). In the case of infeasibility of the new system configuration, new constraints will be iteratively introduced in the energy system models to reach a feasible solution.

Not directly related to the presence of heat networks, in the personal opinion of the author and in addition to what previously discussed, limitations in the diffusion of these methods are connected to two principal aspects: the strong dependence of the results on the economic inputs and on the relevant number of assumptions/data to be managed. Both these aspects require large attention in ensuring the correct interpretation of results. An incorrect interpretation of results may lead to the release of incorrect recommendations with potentially threatening consequences. Even if learning curves and sensitivity analyses may help in reducing the problem, the wide spectrum of new technologies and uncertainties about their cost evolution may have a serious impact on results robustness. The second point related to the large quantity of data and assumptions is most related to the abilities of both the modeller and the analyst to manage and critically analyse them. This re-opens the discussion on the need for greater transparency to make these methods understandable to users and customers. Many researchers are now devoted to creating open data sources and codes, raising concerns on the safe and appropriate use of data. Considering the differences in commercial sensitivity and propriety concerns compared to academic research purposes, a wide debate is concentrated on how to providing open source data and even codes. Indeed, some privacy rule or data selection rule need to be introduced, but the possibility of having larger open data may increase the transparency and therefore the credibility of energy system model results.

As observed, data has a key role in the definition of the model structure as well as on the reliability of model results. On the one hand, the creation of reference standardized datasets on technologies costs and efficiencies may support the definition of a unique framework making results comparable, more transparent and reliable (this is valid on both the global and the local level); on the other hand, at the local level, some data are site-dependent and needs to be specifically available at the municipal level. It was previously introduced which data are required and how its availability impacts on the level of assumptions and the model structure. Nevertheless, the open availability of some of them can be prioritized with respect to others. In the author opinion, Municipalities can start working first on elaborating top-down data in the form of energy balance, fundamental for model calibration, and on bottom-up data related to building volume distributions and characterization. In parallel, the principal data owners can be involved in the data collection and updating process, with the definition of ad-hoc data protocols to further increase the quantity and quality of available data. For the seek of the usefulness of the data, the energy system cadastre as well and energy performance certificates can be extremely useful inputs if made available. Building up this data framework will require consistent analytical abilities and coordinated actions among all major stakeholders and most of all among all the department of the municipality. Besides this, the data collection process is rapidly evolving and improved through the so-called “digital revolution”. New devices, such as smart meters, are spreading to provide information and communication services, increasing real-time “big” data access (traffic flows, electricity consumption, weather data etc.) and potentially able to increase the way to “control” city planning. In this way, long-term approaches will be more and more coupled and constantly updated with more short-term knowledge of the city dynamics managed in data platform that can be used both to inform and to re-think the planning process. Managing all these data volumes will require a higher level of expertise, but also higher energy consumptions. In fact, to these ICT devices, associated energy demand is rapidly evolving, expecting to grow at a rapid rate that needs to be further explored (IEA, 2014).

Another relevant consideration is related to the interactions that urban areas have with respect to their neighbourhoods. Many variables are not strictly dependent on what happens inside the city – also due to the low supply potential inside the city- but are influenced by how the energy system evolves outside the city (e.g., energy prices, carbon emissions from the power sector, resource availability, etc.). This can be represented by justified assumptions as it was done in this thesis or in a more structured way by soft-linking the city model to a national/regional model. However, this strong dependence leads urban results to be strongly constrained by external conditions.

Besides these reflections, the principal learning outcomes, derived from the case study application with respect to heat decarbonization in an urban context, are summarised in the following:

- The proposed methodologies are particularly suitable for heat decarbonization purposes in developed countries. While they are flexible enough to be shaped for developing context they need to be simplified in their level of details and structured to meet specific planning needs: a self-built simulation approach is therefore preferable to an optimization one.

- A very detailed modelling framework, such as the proposed one, may offer several benefits in terms of results, but it may limit its direct applicability to other cities;

- The comprehensive energy system approaches do not seek to replace building simulation or infrastructure operational models further needed to design and implement the energy plans effectively, but they act as a support in the definition of the future system possible configurations.

- From the simulation approach, the impact of building renovation policies on the **operating conditions and investment strategies** for district heating network, and more generally heat strategies, can be derived. It enables explorative scenarios to understand their impacts on the energy system with respect to important economic, environmental and planning considerations.

- From the optimization approach, **consistent opportunities to reach environmental targets and contemporary provide improved building services** can be derived.

- The CO_2 targets can be reached through a mixture of building retrofit measures, solar PV and solar thermal, district heat from low carbon sources together with high efficiency gas and biomass boilers.

- Retrofit measures are extremely important for future decarbonisation pathways. Nevertheless, from a system perspective, sensible district heat investments require building retrofit measures to be cost-effective: large heat savings may not be a cost-effective approach if additional demand by network expansion cannot be used to fully utilise district heating installed capacity.

- Variation of the heat profile would change the size of new investments for base-load plants: new capacity should be planned carefully with respect to anticipated building measures. Heat planning at the local level can make an important contribution to avoiding unnecessary investments.

- Increased electrification in end-use energy services is visible mostly for the reduction of thermal needs and a slight increase of electricity demand (mainly space cooling), such as through heat pumps covering parts of the thermal demand and with a decarbonized power sector (indirectly catch).

- Scaling up the perspective from a single building level to an energy system level would help to capture interdependencies between supply and demand that may lead to identifying business strategies and urban energy plans that avoid unnecessary investments.

- An integrated and comprehensive framework provides a more informed assessment of the appropriate investments, their life-cycle costs and energy and environment ambitions. In particular, finding synergies between energy saving measures and new investments in the heat supply mix has many advantages such as supporting the appropriate balance between energy efficiency improvements and heat electrification.

- The benefits of integrated and comprehensive approaches are particularly visible in cities with district heating where beyond certain levels of demand reduction, the economic benefits of building renovation start to decrease and in some cases may not be cost-effective. Deploying building retrofit in synergy with low carbon technologies can instead reduce the environmental impacts at a reasonable added cost or maintaining a lower system cost depending on decarbonisation target.

- The important role of retrofit measures is stressed. However, their real implementation is dependent from multiple variables such as the willingness to invest of citizens, their age, the property of the building (in particular for high rise buildings) and the policy to support their penetration.

- Renewable technologies and in particular solar technologies clearly play an important role: in general, their deployment in urban areas will depend on urban form and density, and the evolution of electricity grid as well.

- The proposed methodology may highlight opportunities to re-think current building policies to support the progressive decarbonisation of the heat supply sector (e.g., utility companies may propose building renovation measures coupled with new connections to DH networks).

Concerning this last point, as previously said, some of the policy measures available to policymakers can be integrated into the modelling analysis such carbon taxes, building/appliances standards, financial instruments present at the national level or taken as the reception of national/international GHG goals as in case of environmental targets. Most of the policies are defined externally to urban areas and can be modelled as constraints or additional inputs. Nevertheless, some policies can be defined at the local level: in this case, planning models can test them and support their definition. At the local level, policy measures may involve measures on land use, urban form, public/municipal buildings and vehicles (e.g. traffic zones, emission standards, schemes for building efficiency, procurements etc.) or utilities (e.g. new investments in infrastructure or renewable targets), transportation infrastructures, but also specific regulations for building renovation, waste management, renewables in buildings and parking fees etc. Other measures, such as awareness/education campaign or capacity building, can only be included indirectly in the modelling activities. Energy and sustainability goals are influenced by all urban measures and it might be useful to include them into broader urban development policies.

7.2 From a system perspective to decision aiding: from Phase II to Phase III and future works

From the thesis' results, it emerged that comprehensive energy system models can provide analytical support to decision makers in order to assess energy technology strategies and policy assessments. This support is useful to include all the complex interactions of components, but still needs additional efforts to be more frequently and widely incorporated in the urban decision-making process. This Section is dedicated to explaining how the methodology presented in this thesis fits in the urban energy planning procedure.

At the end of the "Detailed Energy Modelling Phase", a bunch of alternative energy scenarios, eventually including potential policy options, are available. In the Decision Making phase, a strategy to be implemented needs to be prioritized.

For further proceeding to Phase III of the procedure (Decision Making), two main actions need to be undertaken: (i) the translation of system perspective actions to stakeholders oriented ones and (ii) the translation of aggregated actions into spatially disaggregated ones.

To shift from a system perspective to a stakeholder-oriented one, again, all the stakeholder groups need to be involved. The available options should be presented in an easy and transparent way to be understandable. The stakeholders' involvement, through well-known techniques (dos Muchangos et al., 2017; Hein et al., 2017), should include all the energy nexus actors and it may lead to further recalculation to adjust the solutions to their requests, possibly starting an iterative loop with the "Detailed Energy Modelling Phase". Also, the scenarios should be translated into more concrete alternatives to be evaluated. This involves a spatial disaggregation of results, even if not as detailed as in the "Operational Phase" (where the alternative to prioritize is already selected and designed). To ease this step, the actions of the scenarios can be separated taking into account their nature (private or public), their sector and the interactions with other sectors and according to the time setting.

Then, once a clear and agreed list of alternatives emerges, a very common methodology used to support the Decision Making phase in a structured way is represented by Multi-Criteria Decision Aiding (MCDA) methods. They are well-known decision support techniques used to aid decision makers in defining better decisions. The MCDA procedure is well explained in (Pohekar and Ramachandran, 2004; Wang et al., 2009): after the problem statement and alternative definitions, MCDA methods continue with the identification and evaluation of criteria (indicators to be measured), both qualitative and quantitative. The choice of the correct set of criteria is very important since they are the values on which recommendations will be derived. Subsequently, the weights ("Importance") of criteria are expressed to show their influence on the criteria performance. Afterward, the performance matrix (the values of alternatives against every criterion) can be structured. Conclusively, after selecting the appropriate method (Huang et al., 1995), MCDA can assess and evaluate the alternatives in order to rank/sort/choice/describe them. To ensure the consistency of the obtained result, a sensitivity analysis (i.e., changing weights and preferences) is strongly suggested.

From a meta-analysis of previous literature performed by the author in (Torabi Moghadam, Delmastro et al., 2017) was highlighted that both comprehensive energy system models, as well as their integration with MCDA, are not a common practice, but their application can be beneficial for urban planning practices. In doing this, energy planning can be related to other urban planning aspects (stocks and flows, layout, district renewals, urban form etc.), contributing to sort poor alternatives. In this stage, energy strategies need to be integrated with the other urban objectives (i.e. work occupation, public health etc.)

Then, one alternative will prevail over the others. At this point, it should be transformed into real actions through the "Design" and the "Implementation" stage, by planning them in the detail. As previously suggested, in the Design Phase, new constraints or information may be identified, requiring further adjustments in the energy plan.

There may be bi-directional links among the Detailed Modelling Phase and the Design Phase: future works of this thesis will deep this aspect starting from the proposed case study and focusing on the impact of the proposed solutions on the electricity grid and gas networks, exploring potential options of renewable gases injection in the gas network. This idea is supported by the fact that the progressive decarbonization of the power sector is expected to increase the electrification of energy demand, facing many challenges in terms of grid flexibility, the evolution of storage costs and performances, etc. as well as consumers and buildings distribution systems adaptation. At the same time, natural gas is widely recognised as the fuel for the energy transition. This generates a controversial dichotomy on the evolution of its supply chain: a lot of investment should be put in place to further develop a sector already intended, some when, to be dismantled. What is more, the Italian energy system is highly reliant on the gas network with a large existing infrastructure both at transmission and at the distribution level. Together with the new opportunities offered by the “Renewable gases” production and penetration in the supply chain, the gas sector may play a different and durable role than just the one of the transition. So, with an expected greater penetration of renewable sources on the one hand and the new technological opportunities offered by the gas sector, understanding the possible evolution and role of the gas network in the energy transition is key to channel future investments in both infrastructures (electricity and gas). An analysis on how electricity, hydrogen, biofuels and synthetic fuels can be combined in the most cost-effective way for a more environmentally friendly society can support a better knowledge, a deeper understanding and suggest a proper planning of the future energy transition strategies. Future works will, therefore, be focused on an integrated and multi-sectoral approach for providing both the planning (costs, emissions and capacities) and the technical (e.g. operational) impact of several scenarios, including both the building and transport sector. In the current transition period, studying the long-term role of competing technological options and renewables integration together with their impact on the existing energy infrastructures such as electricity, gas and heat networks can help understanding the potential and the challenges of electrification in building, transport and industry and evaluating, consequently the role of gas and heat networks in this process.

Going on with the planning procedure, the last part of “Monitoring and informing” has the double function of (i) reporting the performance inventories of indicators in order to be compared with benchmark values (are the results of my actions performing as expected?) and (ii) communicating the impacts (hopefully positive) of my actions to the citizens/interested audience. This step can lead to diagnostic of some malfunctions or to identify further improvements/adaptation measures to be suggested. This phase may lead to new iterations in the planning process and even a re-evaluation of the energy plan, providing feedback to the process.

7.3 Originality aspects and key innovations

This Ph.D. dissertation highlighted how a structured interdisciplinary methodological framework could enhance the state-of-art of urban energy planning. In this thesis, a planning procedure that was applied to a specific case study, identified as relevant for research purposes, in order to generate reflections and highlights for future urban energy planning applications. The theme of urban energy planning was faced with attention to cross-sectoral interactions, highlighting the needs of energy system analysis when applied to urban planning and fitting them into the evolving paradigm of urban energy planning. The whole procedure presented in the thesis is original in its structure from the data collection phase to the detailed modelling one.

All the comprehensive energy system models are characterized by novel structures to specifically fit urban necessities. In fact, the proposed comprehensive energy system models were structured to fit the urban contexts and their outcomes allow preparing a theoretical frame to compare their major characteristics. All the presented comprehensive models were developed from scratch and they are new in their structure. The definition of the models' structure was defined according to the specific planning objective and data availability and not by using traditional templates. The building module in the simulation approach was structured in order to catch the differences in building typologies for the energy and costs analyses, supporting a spatial re-disaggregation of results and, at the same time, a more targeted definition of building retrofit policies. In the heat generation mix model, every heat generation plant was described individually, allowing very precise considerations about their replacement and cost analysis. The integration of the two modules allowed detailed scenarios to be built up in both demand and supply. The optimization model was GIS-driven and temporally resolved to specifically consider disaggregated residential building energy profiles and retrofit options. The developed structure allowed the user to reflect on the possibility of certain technologies to penetrate according not only to their costs and environmental benefits, but also to their compatibility with building age. The thesis was structured in order to show the differences between simulation and optimization frameworks, the differences between a home-built model and a model generator and also to show the precise steps to expand the reference energy system structure, providing insights for future applications.

The addressed research theme studied the competition between building retrofit strategies and heat provisions, starting from the interactions with district heating and then proposing a broader decarbonization perspective, offering new outcomes on the potential synergies between building retrofit, heat strategies and electricity balancing.

The proposed methodological framework is built upon existing approaches, adapted and combined to deliver a first-level assessment of the appropriate combination of methods within a more integrated energy system planning. For building energy modelling, while different existing well-known approaches were applied, novelties on how to apply them were proposed during the thesis. For instance, the Reference Building approach and the cost-optimal method were used in order to be scalable in an urban context, providing original outcomes. This allowed scaling up the results of an individual residential building retrofit model by a volume weighting function in terms of both energy consumptions, but also costs. In the thesis, both the case of building energy modelling with large data availability (residential) and low data availability (non-residential buildings) was shown.

More general innovative aspects, referred to the methodological approach, to the proposed procedure and to the application field, are further reported.

- The application field

Energy system comprehensive models have been traditionally applied on a large scale, while the application on an urban scale required multiple interactions with other methodologies and a high disaggregation level of the models themselves. The models were structured in order to guarantee the necessary level of disaggregation of demand for local analysis. Outcomes of the scenario analyses provided the numerical evidence of the suitability of such approaches for urban applications, nevertheless highlighting that they cannot be used alone for urban applications.

- The methodological approach

Traditionally, urban energy planning practices focused on a single sector approach, while in this thesis an interdisciplinary methodology that combines building physics with cross-sectoral energy planning and territorial analyses is proposed to provide advancements in the field. The competition between retrofit options, individual heat generation solutions, distributed generation technologies, district heating network and storage has been studied by applying well-known existing methodologies as well as by introducing novelty aspects under energy, financial and environmental perspective.

- The procedure

The thesis provides a methodological framework, composed of multiple phases inspired by (Mirakyan et al., 2009), that can be used as a support/guideline for future urban applications. The proposed procedure assists the reader from data collection to the modelling phase and further explains how the proposed procedure can be extended to cover the whole planning and operational stages. Indeed, the energy planning procedure as proposed by (Mirakyan et al., 2009) is here divided it into the interrelated **planning and operational stage**. The planning stage includes the major actions of knowing / understanding / planning/ prioritizing / deciding to be iterated, repeated and improved during the process until a strategy or “energy plan” is defined. It is then possible to further proceed with the operational stage that involves the implementation of the energy planning strategy by designing / acting / monitoring / informing.

Furthermore, innovative aspects are also evident in the GIS-based data collection process and priority identification with a direct involvement of stakeholders in private interviews or public survey through the organization of workshops and individual meetings.

Chapter 8

Conclusions

This Ph.D. dissertation has drawn on the understanding of urban energy planning procedures towards more sustainable development of the urban built environment. While many energy modelling approaches have been recently developed to face the urban energy challenge, a unique structured methodological framework is not available or agreed on among the several experts and scientific disciplines dealing with sustainable urban energy planning.

Given the complex nature of urban energy planning, the identified relevant research questions were answered (Chapter 7) by applying an interdisciplinary and integrated methodological procedure - based on the actions of knowing, understanding and planning. The procedure was applied to a case study that fixed the research boundaries to the demand and supply side of the urban built environment of district heated cities. The case study, on the one hand, provides numerical evidence to results and on the other hand offers a theoretical background for guiding urban planners, researchers and decision-makers in future urban planning applications. Without seeking to replace other existing modelling approaches and without presupposing a full knowledge in the different disciplines, this thesis attempts to provide a basis for understanding how the weaknesses of the different approaches can be rectified by the strengths of others in order to move beyond traditional urban energy planning applications. From the thesis, it is indeed possible to derive insights for the choices among the summarized individual approaches in building physics and energy planning, by highlighting their main characteristics. In order to support the effective integration of methods, current technical limitations and application barriers of approaches were highlighted to raise the awareness of users on the approaches' advantages and limitations. Since no approach is generally preferable than another, the thesis provides the theoretical understanding to recognize which methods better fit a specific planning goal.

The benefits of the proposed integrated approach were extensively stressed throughout the thesis; in particular by highlighting that an integrated and comprehensive framework provides a more informed assessment of the appropriate investments, their life-cycle costs and energy/ environment ambitions.

The author suggested reinforcing the integration between different research disciplines dealing with environmental, financial, technical and in future also social/human aspects with particular attention to spatial issues. Although the approaches have not yet been integrated in order to cover and accomplish all the urban planning procedure, it is important to push future research and practice to take into account the integration process divided into a planning stage (knowing & understanding/ planning/ prioritizing & deciding) and into an operational stage (designing/acting/monitoring & informing). From the thesis emerged the frequently misleading concept that while the planning phase represents a support in investing responsibly in alternative consumption patterns and greener strategies, the operational stage supports the effective implementation of the strategy. The thesis highlight that while moving from energy planning (pre-design) to the design phase, comprehensive energy system models will need to be combined with operational modelling framework to solve the temporal resolution problems and to better catch the relationship between heat and electricity systems or infrastructure evolutions. This may lead to a bi-directional flow of information between planning and operational models highlighting a first future challenge related to the interoperability of models. Other major future challenges are mostly related to barriers related to the potential applicability of such a complex and integrated procedure: the need of changing traditional thinking and habits, the required time, high level of expertise and costs to perform the complete planning process, the need of high-level data (quantity and quality) and the necessity of transparency on input data, assumptions and results to be understandable to decision-makers.

Key-words in urban planning applications are, therefore: long-term, to take into account infrastructure evolutions, market-evolutions and investments pathways; spatial, to guarantee the territorial level of analysis; comprehensive, to catch the cross-sectoral interactions; data availability and quality, to ensure the robustness and consistency of models; stakeholders' involvement, to offer a shared city vision and framework and to strengthen the collaboration and relationship between research and local private and public authorities.

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Torabi Moghadam, S., Delmastro, C., Corgnati, S.P., Lombardi, P., 2017. Urban energy planning procedure for sustainable development in the built environment: A review of available spatial approaches. J. Clean. Prod. 165. doi:10.1016/j.jclepro.2017.07.142

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Nomenclature

Abbreviations:

AB: Apartment Block

C1-C9: Contruction periods of buildings

CHP: Combined Heat and Power (Co-generation)

CT: carbon tax

DH: District Heat

DL: decarbonization level of the power sector

DR: Discount Rate

ET: Environmental targets

FP: Fuel prices

H1-3: heating season

HDD: Heating Degree Days

HOB: Heating Only Boiler

LP: Linear Programming

MF: Multi-family buildings

MSW: Municipal Solid Wastes

NH: non-heated season

O&M: Operation and Maintenance (Costs)

RB: Reference Buildings

RES: Reference Energy System

RES_P: renewables penetration

S1/2: Scenario 1/2

SEAP: Sustainable Energy Action Plan

SF: Single family buildings

TAPE: Turin Energy Action Plan

TH: Terraced houses

WD: Week Days

WE: Week-end Days

Symbols:

$C_{g,b}$ (€/m^3): global cost at single building level referred to the base year of the analysis (t=0) considering a calculation period t;

C_{Inv} (€): investment cost at the year t=0;

C_y (€/y): yearly cost related to a building component (O&M, running cost, substitution cost);

d: present value factor;

R_f (€): residual value of a building component;

$V_{REN,\,TOT}$ (m^3): renovated volume from 2010 to 2050;

$V_{EX,\,TOT}$ (m^3): existing not renovated volume at the beginning of a time step;

r (%): renovation rate of building type;

$C_{G,BS}$ (€): global cost of buildings (2050) discounted at 2015 level ;

$O\&M_a$ (€/y): yearly O&M cost for a building archetype in a time step;

$C_{e,d}$ (€/y) : fuel cost relative to a building archetype in a time period;

RV (€): residual value of the investment for a building archetype;

LCOH (€/kWh): discounted levelized cost of heat;

C (€): fuel cost, running and fix O&M for the plants, O&M for the distribution network, connection costs relative to a time period;

E_{DHtot} (kWh): delivered heat from DH;

$C_{G,dh}$ (€): total discounted life-cycle cost of the DH system;

$C_{INV,dh}$ (€): investment costs in new DH capacity;

$CO_{2eq,dh,tot}$ (t): total CO_2 equivalent emissions to 2050;

$CO_{2,eh,xj}$ (t/h): carbon equivalent emission from heat plant *x* in hour *j*;

$E_{plant,x,j}$ (kWh/h): heat produced from plant x in hour *j* considering the merit order of plants, the demand variation and the availability of the plant (no variation in the electricity to heat quota have been considered);

TSC (€): total discounted life-cycle cost considering the energy cost, investments new DH capacity and investments in energy conservation measures in buildings;

$CO_{2eq,b,tot}$ (t): CO_2 equivalent emissions to 2050 related to the heat production at the building level;

$CO_{2,tot}$ (t): total equivalent carbon emissions to 2050.

Annex A

This Annex lists the papers published during the Ph.D. activity that have been relevant for the thesis activity. The author's contribution in the papers is highlighted.

Paper	Details
I	Torabi Moghadam S., ***Delmastro C.***, Corgnati S. P., Lombardi P. (2017). Urban energy planning procedure for sustainable development in the built environment: A review of available spatial approaches. **Journal of Cleaner Production**, 165, 811-827.
II	***Delmastro C.***, Mutani G., Corgnati S.P. (2016). A supporting method for selecting cost-optimal energy retrofit policies for residential buildings at the urban scale, **Energy Policy**, 99, 42-56.
III	Becchio C., Corgnati S.P., ***Delmastro C.***, Fabi, V., Lombardi, P. (2016). The role of nearly-zero energy buildings in the transition towards Post-Carbon Cities, **Sustainable Cities and Society**, 27, 324-337.
IV	Mutani, G., ***Delmastro, C.***, Gargiulo, G., Corgnati, S.P. (2016). Characterization of building thermal energy consumption at the urban scale, **Energy Procedia**, 101, 384-391.
V	Torabi Moghadam, S; ***Delmastro, C***; Lombardi, P; Corgnati S P (2016) Towards a New Integrated Spatial Decision Support System in Urban Context. **Procedia: Social & Behavioral Sciences**, vol. 223, 974-981.
VI	***Delmastro, C.,*** Martinsson, F., Dulac, J., Corgnati, S.P. (2017). Sustainable urban heat strategies: perspectives from integrated district energy choices and energy conservation in buildings. Case studies in Torino and Stockholm. **Energy**, 138, 1209-1220.
VII	***Delmastro C.,*** Mutani G., Perassi, S. (2016). In use monitoring of public buildings. Case study in North Italy. **International Journal of Heat and Technology**, 34 (2), 266-276.
VIII	***Delmastro C.***, Martinsson, F., Mutani, G., Corgnati, S.P. (2017). Modeling building energy demand profiles and district heating networks for low carbon urban areas. Procedia Engineering, 198, 386 – 397.
IX	***Delmastro C.***, Lavagno E., Schranz L. (2016). Underground urbanism: Master Plans and Sectorial Plans. **Tunnelling for Underground Space Technology**, 55,103-111.
X	Borchiellini, R.; Corgnati, S.P.; Becchio, C.; ***Delmastro, C.***; et al. (2017). *The Energy Center Initiative at Politecnico di Torino: Practical experiences on energy efficiency measures in the municipality of Torino.* ***International Journal of Heat and Technology***, 35 n. Specia, 196-204.

Paper I

The author share the responsibility with Sara Torabi Moghadam for the whole content of the paper, with exception of paragraph 3.2.3 developed by the author and paragraph 3.3 developed by Sara Torabi Moghadam.

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Review

Urban energy planning procedure for sustainable development in the built environment: A review of available spatial approaches

Sara Torabi Moghadam [a], Chiara Delmastro [b, *], Stefano Paolo Corgnati [b], Patrizia Lombardi [a]

[a] Interuniversity Department of Regional and Urban Studies and Planning, Politecnico di Torino, Viale Mattioli 39, Turin 10125, Italy
[b] Department of Energy, Politecnico di Torino, C.so Duca degli Abruzzi 24, Turin 10129, Italy

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Spatial decision support system

A B S T R A C T

Urban and Regional Integrated Energy Planning is crucial to define transition strategies toward sustainable development and post-carbon cities; particularly, in the built environment sector which is one of the main responsible for energy consumption and carbon emissions.

The paper aims at offering a systematic review of existing urban and regional energy planning approaches. This analysis is based on literature review. The reviewed papers are critically analyzed and discussed through a Meta-analysis and a SWOT analysis. The papers are classified in order to highlight the main research trends and to illustrate the most relevant characteristics of the principal approaches.

This critical analysis of the papers highlights the lack of an holistic and integrated framework which is able to take into account the large variety of dimensions related to sustainable planning. A major achievement of this study is to provide information on how the various existing approaches can be integrated to handle the entire planning procedure adequately.

The result provides a preliminary theoretical framework to integrate different approaches, identify the main barriers and future challenges in the field of research. This framework will help urban actors to develop energy planning projects, guiding them in the choice among a significant number of existing planning approaches.

Paper II

The author is responsible for the whole content of the paper, with exception of the socio-economic analysis under the responsibility of Guglielmina Mutani. Building volumes were derived from the work of (Mutani and Paírona, 2014).

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Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

A supporting method for selecting cost-optimal energy retrofit policies for residential buildings at the urban scale

Chiara Delmastro *, Guglielmina Mutani, Stefano Paolo Corgnati

Department of Energy (DENERG), Polytechnic of Torino, 10129 Torino, Italy

HIGHLIGHTS

- A bottom-up methodology to aid decision-making in the planning process is presented.
- The approach simulates the stock evolution from an energetic, social and economic perspective.
- Identifying buildings to be prioritized can significantly reduce the global cost on the long-term.
- The energy savings potential of the stock can be evaluated through the cost-optimal methodology.
- Socio-economic analysis is crucial to understand the attended perception of a policy by investors.

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ABSTRACT

Nowadays, in Europe, the main challenge is not only the construction of new high performing buildings, but also the promotion of proper retrofit actions on existing buildings. In the on-going transition towards low carbon cities, tools to support local municipalities are fundamental.

To scale up results achieved at single buildings to group of buildings and to reflect the dynamics of the buildings stock with acceptable computational costs, new approaches are needed.

This paper presents a new bottom-up methodology to aid decision-makers in the planning process; the approach enables to simulate and analyse the evolution of the building stock from an energetic, economic and social perspective over long-term horizons. The approach is based on analytic hybrid methodologies for building energy performances assessment and on Geographic Information System for the creation of a database and thematic maps. In particular, the approach: 1) identifies the cost-optimal mix of successful renovation packages; 2) identifies buildings that needs to be prioritized; 3) considers the impact of socio-economic factors on policies implementation. The method is validated through urban calibration coefficients dependent on the city energy balance.

Results show that this approach can support different stakeholders in selecting specific strategies depending on the desired goals.

Paper III

The authors share the responsibility of the paper. In particular, the author is responsible of Section 4.

Sustainable Cities and Society 27 (2016) 324–337

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journal homepage: www.elsevier.com/locate/scs

The role of nearly-zero energy buildings in the transition towards Post-Carbon Cities

C. Becchio[a], S.P. Corgnati[a,*], C. Delmastro[a], V. Fabi[a], P. Lombardi[b]

[a] DENERG—Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy
[b] DIST—Politecnico di Torino, viale Mattioli 39, Torino 10125, Italy

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nZEB
Occupant behaviour
Scenarios analysis
Energy planning

ABSTRACT

Nowadays about 50% of global population lives in cities, responsible for about 70% of GHG emissions and by 2030 the urbanization rate will increase to over 75%.

The paper analyses the new emerging concept of "Post-Carbon City" (PCC) and its main influencing factors regarding the building sector. It provides inspiration to re-think urban re-development patterns leading the way for new comprehensive approaches. In this new vision, energy and cost-effective retrofit of existing buildings cover a key role both in terms of saving potential and emission reduction towards nearly-zero energy building (nZEB) target. Moreover, in the building operational phase occupant behaviour has a strong impact on the real energy performance and its effect should be minimized. Therefore, these two issues should be mainly taken into account when energy city planning. Several mid/long-term scenarios analyses performed through quantitative energy demand forecasting tools – concerning not only the building sector, but the whole energy system – are the only opportunity to produce indications for an energy-oriented city planning. Finally, it highlights the necessity of new Advanced Input Modelling procedures to improve the effectiveness of measure recommendations derived through scenarios analysis.

Paper IV

The authors share the responsibility of the content of the paper. The author is responsible of paragraph 2.1, Guglielmina Mutani is responsible of paragraphs 2.2 and 2.3. Building volumes refer to the work of (Mutani and Pairona, 2014).

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71st Conference of the Italian Thermal Machines Engineering Association, ATI2016, 14-16 September 2016, Turin, Italy

Characterization of building thermal energy consumption at the urban scale

Guglielmina Mutani [a], Chiara Delmastro [a*], Maurizio Gargiulo [b], Stefano P. Corgnati [a]

[a]DENERG, Politecnico di Torino, C.so Duca degli Abruzzi, 10124 Torino, Italy
[b]E4SMA, Via Livorno 60, ENVIRONMNET PARK, Torino, Italy

Abstract

The ongoing urban transition toward decarbonized energy systems has raised the attention on local energy planning practices. Besides the multiple actors involved in the planning process, the complexity of the urban energy systems requires the elaboration of heterogeneous data. In such contest, the paper introduces and compares two GIS-based methodologies for supporting the spatial characterization of the local residential built environment in terms of building distribution and space heating energy consumption. Starting from the assessment of residential consumption, a third method for the characterization of non-residential building thermal energy consumption is proposed. From a bottom-up perspective, in both residential models all the buildings are geo-referenced and clustered according to their thermo-physical characteristics. From a top-down perspective, energy balance data are used to calibrate the bottom-up results and to match the total building loads. The procedure, tested on the city of Turin as case study, allows assessing the energy use of buildings and to create urban energy maps.
The energy spatial characterization of a territory is the basis for performing short and long-term scenarios analysis. Results of this method can be useful to: i. decision maker to understand the current state of the territorial energy consumption to identify critical energy intense areas; ii. citizens for visualising their energy consumption and iii. researchers for setting up the basis of further urban analysis.

Peer-review under responsibility of the Scientific Committee of ATI 2016.

Keywords: building stock; urban; energy modeling; GIS; space heating

Paper V

The authors share the responsibility of the content of the paper.

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Procedia Social and Behavioral Sciences

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Towards a New Integrated Spatial Decision Support System in Urban Context

Sara Torabi Moghadam[a,*], Chiara Delmastro[b], Patrizia Lombardi[a], Stefano P. Corgnati[b]

[a]*Interuniversity Department of Regional and Urban Studies and Planning, Politecnico di Torino, Viale Mattioli 39, Turin 10125 Italy*
[b]*Department of Energy, Politecnico di Torino, Corso Duca degli Abbruzzi 24, Turin 10129, Italy*

Abstract

The current growth of urbanization rate indicates that this trend is not going to stop, and therefore, it stresses the necessity of actions for mitigating the local and global pollution. Moreover, most of the actual stock is characterized by low energy performances since it pre-dates the energy regulation. The paper aims at addressing this issue by proposing the integration of Building Simulation (BS) approach, Multi-Criteria Analysis (MCA)methods and Geographic Information System (GIS)tool for developing a newMulti-Criteria Spatial Decision Support System (MC-SDSS)in urban context. The BS of relevant building archetypesallows to identify different resolutions of energy data: hour-by-hour data can be useful for demand-side management or renewable integration while aggregated data can be used for load forecasting and retrofit simulations. TheMCApermitschoosing between different building renovation alternatives by considering both qualitative and quantitative criteria.Moreover, the GIS support the method by creating geo-referenced databases.The methodpurposes in giving a comprehensive view to address the complexity of urban building energy planning; due to its flexibility, it can be applied to several urban areas. Three main phases characterize the study: i. overview of relevant existing techniques; ii. description of the integrated proposed method; iii. discussion and future application. The method can provide relevant feedbacks for ranking complex design energy options.

Peer-review under responsibility of the organizing committee of ISTH2020

*Keywords:*Geographic Information System (GIS);Building Simulation (BS);Multi-Criteria Spatial Decision Support Systems (MC-SDSS); Urban Energy Planning

Paper VI

The author is responsible for the Torino case study and share the responsibility with Fredrik Martinsson for the definition of the modelling approach.

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Sustainable urban heat strategies: Perspectives from integrated district energy choices and energy conservation in buildings. Case studies in Torino and Stockholm

CrossMark

C. Delmastro [a, *], F. Martinsson [b], J. Dulac [c], S.P. Corgnati [a]

[a] Department of Energy, Politecnico di Torino, C.so Duca degli Abruzzi, 10129, Torino, Italy
[b] Swedish Energy Research Centre – Energiforsk, Olof Palmes gata 31, 10153, Stockholm, Sweden
[c] International Energy Agency, 31-33 rue de la Fédération, 75739, Paris, France

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Urban heat strategies
Energy planning

ABSTRACT

Heat demand in buildings is responsible for a large portion of energy loads in Europe, and building renovations represent an important opportunity to achieve sustainability objectives. Efficient district heat (DH) can represent a cost-effective heat source for buildings. Yet, building heat demand reductions will have implications on sustainable DH production and operation. Analysis is therefore needed to identify cost-effective strategies for low-carbon heat solutions in integrated energy systems.

This paper proposes a methodology to investigate different scenarios to 2050 involving integrated heat supply and building envelope investment choices in Torino, Italy and Stockholm, Sweden. The goal is to provide an overview of opportunities for decision makers in elaborating heat strategies including DH.

Results show that opportunities exist to achieve consistent energy savings and emissions reduction through strategic combination of DH and building renovation investments.

A systems approach is essential to avoid unnecessary investments or early retirement of assets: building renovations should be planned carefully as lower DH base loads could lead to increased running costs, and DH investments need to be adapted to long-term building improvements. Reduced peak loads can allow increased use of low-grade heat, higher merit-order power generation and in some instances cost-effective expansion of DH.

Paper VII

The work derives from the Master thesis activity of Stefano Perassi. The authors share the responsibility for the content of the thesis.

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In Use Monitoring of Public Buildings. Case Study in North Italy

Chiara Delmastro *, Guglielmina Mutani and Stefano Perassi

Politecnico di Torino, Department of Energy, C.so Duca degli Abruzzi 24, 10129, Torino

Email: chiara.delmastro@polito.it

ABSTRACT

Urban areas have become energy intensive hubs that need of solutions for significantly reduce carbon emission in the next decades. For that reason, the exploration of different energy conservation measures alternatives is crucial for meeting the desired environmental goals.
In such contest, the paper proposes a procedure, based on real-time monitored data, for characterizing the thermal and electric consumption of urban public buildings (schools, offices, etc.). The paper aims at providing rich information about the building performances and occupation schedules for finding opportunities for better control/regulation/energy service contracts strategies for operating public buildings.
The procedure is applied to case study buildings in Rivalta di Torino and demonstrates that most of buildings can really benefit from this analysis leading to a more comfortable work environment and contemporary reducing their energy consumption at an affordable cost.

Keywords: Public buildings, Monitoring, Diagnostic, Energy conservation measure.

Paper VIII

The author is responsible for the Torino case study and share the responsibility with Fredrik Martinsson for the definition of the modelling approach.

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Modeling building energy demand profiles and district heating networks for low carbon urban areas

Chiara Delmastro[a,*], Fredrik Martinsson[b], Guglielmina Mutani[a], Stefano P. Corgnati[a]

[a] Department of Energy, Politecnico di Torino, C.so Duca degli Abruzzi 24, Torino 10129, Italy
[b]IVL Swedish Environmental Research Institute, Valhallavägen 81, 114 27 Stockholm, Sweden

Abstract

Urban energy consumptions growth has become an urgent topic that requires solutions for significantly reduce carbon emission in the next decades. This paper aims in exploring the integration of building performance improvement and low carbon district heat technological choices by considering the upgrade of conversion technologies, efficiency and the exploitation of local resources.

The paper is based on a GIS-based model that spatially characterize the space heating demand of urban buildings. Starting from clustering buildings with similar thermo-physical characteristics, the total energy use of buildings can be depicted and compared with the energy balance data of the city in order to scale the bottom-up results for matching the total load. Reasonable energy efficiency measures are further proposed by considering three different scenarios up to 2050. Long-term building scenarios are applied to a district heating simulation model for investigating how the reduction of building heat demand will impact the district heating production and operations. In particular, the combination of the building model and the district heating model aims at exploring the effects of district network expansion or new low carbon investments from an economic and environmental perspective. The model has been successfully applied to the city of Turin, Italy and the city of Stockholm, Sweden. The flexibility of the approach may allow it to be easily adjusted to different urban areas for providing indications on cost-effective strategies for efficient, low-carbon heat solutions in integrated energy systems. Results highlight that finding synergies between the demand and supply sector will lead to environmental and economic benefits, in particular for district-heated cities.

Peer-review under responsibility of the organizing committee of the Urban Transitions Conference

Keywords: urban planning; heat strategies; buildings; district heating network; scenarios analysis

Paper IX

The authors share the responsibility for the content of the paper.

Tunnelling and Underground Space Technology 55 (2016) 103–111

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Underground urbanism: Master Plans and Sectorial Plans

Chiara Delmastro *, Evasio Lavagno, Laura Schranz

Energy Department, Politecnico di Torino, Corso Duca deli Abruzzi 24, 10129 Torino, Italy

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Urban areas
Urbanism

ABSTRACT

The urbanization process leads many urban areas and megacities to be densely built and to overcome their physical and operational limits; in several cases, urban population density is growing faster than their infrastructures. Considering land use constraints, for mitigating some disagreeable living conditions and for creating new population opportunities, city planners have different opportunities involving the two opposite vertical directions: upward, erecting higher buildings or downward, developing a more intense use of the underground space. Both directions are characterized by positive and negative aspects and require suitable local condition to be built.

In this paper, main issues related to the urban underground planning procedures are highlighted, taking also in consideration that after some very old visionary approaches, no relevant debates and concrete results have been further developed. Several underground-related technicalities are described and analyzed, mainly at sectorial level (f.i. mass transport systems, infrastructures for energy and water supply, storage facilities) however, experiences of a global urban planning – involving a holistic approach inside a City Master Plan – are still very few (Helsinki). A collection of some best practices is reviewed in this paper. Particular emphasis is devoted to the integrated planning approach and the related tools for the subsurface space assessment: the role of different planning tools for the rational use of the underground space in urban areas is analyzed and a variety of planning levels are discussed, from the more general one – the Master Plan – to the more sectorial ones. Moreover, the more recent visions for future cities – Smart, Resilient, Low-carbon and Post-Carbon Cities – are producing relevant and very useful technical and management solutions and the role of Integrated Mater Plans in this transition is further discussed.

Paper X

The authors share the responsibility for the content of the paper. The author is responsible for paragraph 2.1.

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The Energy Center Initiative at Politecnico di Torino: Practical experiences on energy efficiency measures in the municipality of Torino

Romano Borchiellini, Stefano P. Corgnati, Cristina Becchio, Chiara Delmastro, Marta C. Bottero, Federico Dell'Anna, Andrea Acquaviva, Lorenzo Bottaccioli, Edoardo Patti, Ettore Bompard, Enrico Pons, Abouzar Estebsari, Vittorio Verda, Massimo Santarelli, Pierluigi Leone, Andrea Lanzini*

Energy Center Lab, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129, Torino, Italy

Email: andrea.lanzini@polito.it

ABSTRACT

Urban districts should evolve towards a more sustainable infrastructure and greener energy carriers. The utmost challenge is the smart integration and control, within the existing infrastructure, of new information and energy technologies (such as sensors, appliances, electric and thermal power and storage devices) that are able to provide multi-services based on multi-actors and multi and interchangeable energy carriers. In recent years, the Municipality of Torino represents an experimental scenario, in which practical experiences in the below-areas have taken place through a number of projects: 1. energy efficiency in building; 2. smart energy grids management and smart metering; 3. biowaste-to-energy: mixed urban/industrial waste management with enhanced energy recovery from biogas. This work provides an overview and update on the most interesting initiatives of smart energy management in the urban context of Torino, with an analysis and quantification of the advantages gained in terms of energy and environmental efficiency.

Keywords: Biowaste-to-Energy, Energy Efficiency, Urban Environment, Energy Planning Policies.

Other Publications

During the three years Ph.D. activities other publications, not directly related to this thesis, are here summarized:

Kazmi, H., D'Oca, S., Delmastro, C., Lodeweyckx, S., Corgnati, S.P. (2016). Generalizable occupant-driven optimization model for domestic hot water production in NZEB. **Applied Energy**, vol. 175, pp. 1-15. - ISSN 0306-2619. DOI: 10.1016/j.apenergy.2016.04.108

Delmastro C., Lavagno E., Schranz L. (2016). Energy and Underground, **Tunnelling for Underground Space Technology**, vol. 55, pp. 96-102, ISNN: 08867798, DOI: http://dx.doi.org/10.1016/j.tust.2015.10.021

Delmastro C., Mutani G., Schranz, L., Vicentini, G. (2015). The role of urban form and socio-economic variables for estimating the building energy savings potential at the urban scale. **International Journal of Heat and Technology**, vol. 33 (4), pp. 91-100. ISSN 0392-8764, DOI: http://dx.doi.org/10.18280/ijht.330412.

Delmastro C., Mutani G., Schranz L. (2015). The evaluation of buildings energy consumption and the optimization of district heating networks: a GIS-based model. **International Journal of Energy and Environmental Engineering**, 7, pp. 343-351. ISSN 2008-9163, DOI: http://dx.doi.org/10.1007/s40095-015-0161-5

Delmastro C., Mutani G., Schranz L. (2015). Advantages of coupling a woody biomass cogenartion plant with a district heating network for a sustainable built environment: a case study in Luserna San Giovanni (Torino, Italy), **Energy Procedia**, vol. 78, pp. 794 – 799. ISSN 1876-6102, doi:10.1016/j.egypro.2015.11.102

Sara, Torabi Moghadam; Delmastro, Chiara; Lombardi, Patrizia; Corgnati Stefano Paolo (2016) *Towards a New Integrated Spatial Decision Support System in Urban Context.* ***Procedia: Social & Behavioral Sciences***, vol. 223, pp. 974-981. - ISSN 1877-0428, doi: 10.1016/j.sbspro.2016.05.334

Delmastro, C., Mutani, G., Pastorelli, M., Vicentini, G. (2015). Urban morphology and energy consumption in Italian residential buildings, Proceedings of the "2015 International Conference on Renewable Energy Research and Applications (ICRERA)", Palermo, 22-25 November. ISBN: 9781479999828, DOI: http://dx.doi.org/10.1109/ICRERA.2015.7418677

Annex B

Reference Energy System

This Annex is dedicated to the developed Reference Energy System relative to the Torino-TIMES model described in Chapter 6.

Annex C

In this annex, the attended courses and seminars are listed.

Ph.D. (third level) courses - Hard Skills

Code	Title	Teacher	Credit	hours
01QUEIV	The future of nuclear energy	Ravetto P.	2	10
01ETLRP	Metodi per il supporto delle decisioni	Norese M.F.	5	25
01QSKIV	Experimental heat and mass transfer	De Salve M.	4	20
01QUGIV	Energy in smart buildings	Corrado V./Corgnati S.P.	2	10
01QSJIV	Energy for future factories	Asinari P.	2	10
01QTVRS	Behavioral theories	Porcello C.	3	15
01QUFIV	Sustainable transport systems: energy and environmental issues	Spessa E.	2	10
01QTEIU	Data mining concepts and algorithms	Baralis E.M.	4	20
01QSNRV	Energy security in EU: Methodological approaches and policy making	To be defined	3	15
01OKGNA	Models and scenarios for energy planning	Zucchetti M.	8	80
01PJMIV	Etica informatica	Patrignani N.	4	20
01PJNIV	Fondi competitivi per la ricerca: dall'idea alla scrittura del progetto	Anfossi A.F.	2	10
01QGBIV	Writing scientific papers in English	Tabacco A.M.	3	15

External Activities

Scuola Estiva di Fisica Tecnica - IX edizione	Università degli Studi del Sannio	30
VEDA - TIMES Basic Level Training Course	IEA ETSAP - UCC Cork University College	20
Summer School on Energy Transitions of the Sino-European Engineering Education Platform (SEEP)	KTH Royal Institute of Technology - Eindhoven University of Technology	45
Summer School "DHC meets ICT" (DHC+)	Politecnico di Torino	30

Research activities outside Politecnico

Case study "Energy conservation and low carbon district heat in Turin"	OECD - International Energy Agency (IEA) - ETP Division	4/5/2015 - 7/8/2015; 15/10/2015 - 13/11/2015